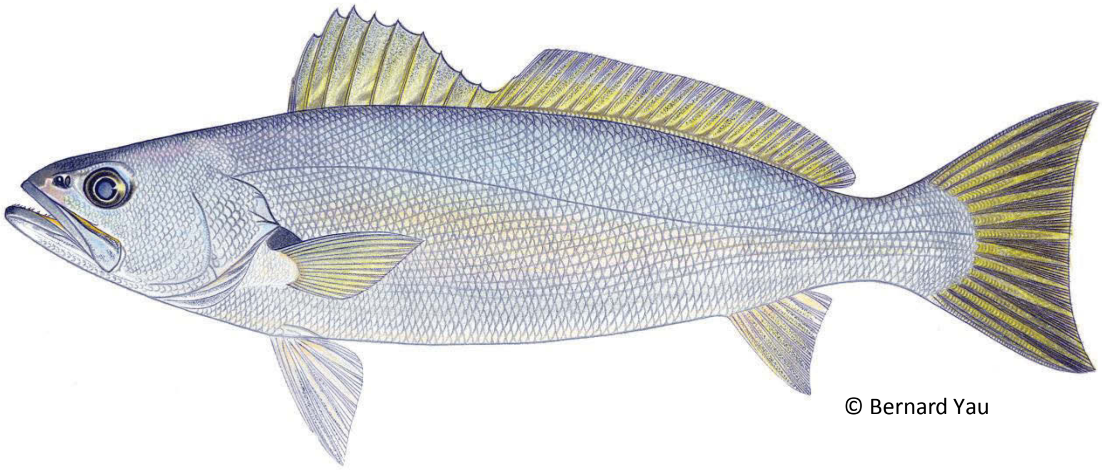
Life History Characteristics and Fishery of Teraglin, *Atractoscion aequidens* in New South Wales, Australia



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Preface

The contents contained within this thesis are my own work with guidance from Professor William Gladstone (University Technology Sydney) and Dr John Stewart (Fisheries NSW). The design of the research presented was personally conceptualised with the guidance of my supervisors.

This thesis contains 5 chapters. Chapters 1 (Introduction) and 2 (Fisheries) are descriptive chapters. Two chapters are data chapters (Chapter 3 and 4) prepared as stand-alone journal manuscripts (unpublished). For this reason there will be some repetition in the content. To prevent unnecessary duplication a single reference list will be provided.

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Thesis Abstract

Teraglin (*Atractoscion aequidens*, family Sciaenidae) is a coastal schooling species of fish found in eastern Australian waters and in the South Atlantic Ocean off the coast of Africa. In Australia, they are found from southern Queensland to Montague Island in southern New South Wales (NSW) in depths of 20-80 m over broken gravel and reef. Despite a long history of exploitation this is the first study of the life history characteristics of *A. aequidens* in NSW where they are targeted by both commercial and recreational fisheries. The aim of this study was to describe age compositions, growth rates, and reproductive characteristics in NSW and to compare results to the other *A. aequidens* populations. Fishery-dependant samples were collected from fishermen's co-operatives at major ports of commercial landings between January 2011 and June 2012. Sampling sites were divided into north (30.30° S, 153.12° E) and south regions (32.18° S, 152.51° E) corresponding to two distinct regions of the East Australian Current (EAC). *Atractoscion aequidens* was found to be fast-growing, reaching approximately 40 cm fork length (FL) in the first year of life with a maximum age in excess of 10 yr. Females were estimated to grow to a larger asymptotic length (84 cm FL) than males (69 cm FL). Length/age at which 50% of the population matures is approximately 35 cm FL and 1 yr. In South Africa, the same species matures at 90 cm FL and 5 yr. In NSW, *A. aequidens* displays year-round batch spawning behaviour with asynchronous oocyte development and indeterminate fecundity. Batch fecundity estimates ranged from 32,431 (± 2,370) for a 43 cm fish to 673,813 (± 2,929) for a 71.5 cm fish. Fish from the south region were on average larger than those from the north. The commercial fishery in NSW is predominantly based on young fish < 3 yr. With the majority of the fishery based on young fish and with the species capable of growing to a relatively large size and old age, there is a concern the species is experiencing an excessive fishing mortality rate. There are many examples of declines of sciaenid fisheries due to lack of life history information. This study of the species' life history characteristics and fisheries provides a basis for development of a quantitative assessment which will contribute to effective management of *A. aequidens* for sustainable fisheries.

Chapter 1: General Introduction

1.1 Research problem

Species within the family Sciaenidae (mulloway, croakers, drums) support many significant recreational and commercial fisheries throughout their distribution and comprise one of the most important groups of food fishes in the world (Paxton and Eschmeyer, 1994). There is concern that stocks of many of these species have collapsed or are severely depleted (Griffiths and Hecht, 1995b; Donohoe, 1997; Sadovy and Cheung, 2003). Sciaenids are particularly susceptible to overfishing due to their restricted geographic ranges and life history characteristics, including formation of spawning aggregations and large size and age of onset of sexual maturity (Sadovy and Cheung, 2003; Potts *et al.*, 2010). Additionally, the large sizes that many of these species attain make them trophy fish, resulting in heavy fishing pressure. Unfortunately, studies investigating the life history characteristics of many of these species have only occurred after long-term population declines (Sadovy and Cheung, 2003).

In Australia, there are similar concerns of heavy fishing pressure on sciaenids (Stewart *et al.*, 2015). Only two species are found in the temperate waters off south-eastern Australia, each from a different genus – teraglin, *A. aequidens* (Cuvier, 1830) and mulloway, *Argyrosomus japonicus* (Temminck & Schlegel, 1843) (Steffe and Neira, 1998). Both species are significant to fisheries in New South Wales (NSW) and Queensland (QLD). *Argyrosomus japonicus* have been extensively studied (Silberschneider and Gray, 2005) and are assessed as overfished (Stewart *et al.*, 2015). Unfortunately, despite the relatively long history of exploitation, there has been no study into the life history characteristics or fisheries of *A. aequidens* off the coast of NSW. However, there are concerns that the stock may be depleted. Anecdotal evidence suggests the schooling and voracious feeding behaviour of *A. aequidens* results in a high proportion of individuals being caught, thus making the species susceptible to overfishing (Stewart *et al.*, 2015). In NSW waters, *A. aequidens* was once a significant component of the recreational and commercial hook and line fisheries. However, the commercial fishery has declined from approximately 200 t per annum in the 1950s to a low of 7 t in 2005/06, with recent landings averaging below 30 t per annum (Stewart *et al.*, 2015). Anecdotally the recreational fishery has suffered a similar decline.

This study will describe the fisheries and investigate the life history characteristics and ecology of *A. aequidens* by sampling at three key locations on the NSW coast. The existence of geographic and temporal variation in age, growth, and reproductive strategies of *A. aequidens* will be investigated in NSW and these parameters will be compared with information available from southern Queensland and South Africa.

1.2 Sustainable Fisheries Management

Biological information such as growth, size and age at maturity, fecundity, age structure and fishing mortality are important for the sustainable management of a stock (Helfman, 2007). There is mounting evidence that the world's fishing resources are under increasing pressure as stocks decline and fishing effort increases (Hutchings, 2000; Pauly *et al.*, 2002; Helfman, 2007; Anticamara *et al.*, 2011). Previous notions of high resilience to fishing pressure due to high fecundity and wide distributions are being proven incorrect with the collapse of some fish stocks and the threat of extinction (Pauly *et al.*, 2002). Life history characteristics for a large number of target species have not been researched since the rapid expansion of fisheries world-wide began in the 1970s. While it has been argued that there are many failings in fisheries management using single-stock assessments only (Pauly *et al.*, 2002), knowledge of the biology of a species is imperative to understanding what pressures can be exerted on a stock and provide the necessary information for stock assessment modelling (Marriott *et al.*, 2011).

Age and growth information on a species are paramount to determining model parameters such as growth rates, longevity, age at maturity and mortality (Lowerre-Barbieri *et al.*, 1996). It is widely accepted that the use of the sagittal otolith is the most accurate method of ageing fish species including many sciaenids (Lowerre-Barbieri *et al.*, 1994; Griffiths and Hecht, 1995b; Silberschneider *et al.*, 2009).

Information on species' reproductive strategies such as age and length at maturity, fecundity, spawning season and spawning frequency are vital for the development of management strategies on a fished stock. While there are over 280 species in the family Sciaenidae, reproductive studies tend to be limited to a small number of species from western countries. E.g. *C. regalis* (Lowerre-Barbieri *et al*., 1995), *C. nebulous* (Bortone, 2003), *Sciaenops ocellatus* (Ross *et al*., 1995), *A. japonicus* (Silberschneider and Gray, 2005).

Many sciaenids are key target species of fisheries world-wide. Evidence exists that the life history characteristics of many sciaenids, results in susceptibility to overfishing and slow recovery from over-exploitation (Sadovy and Cheung, 2003). It is unsurprising that many of the management arrangements for sciaenid recovery have not been successful, as they have not been based on life history information. For example, a spawning closure for the largest sciaenid *Totoaba macdonaldi* was not based on the species' reproductive biology and resulted in very poor management of a heavily targeted stock and subsequent collapse (Potts *et al*., 2010). It is important therefore to research life history characteristics of a species to establish suitable fisheries management.

This literature review begins with an introduction to the family Sciaenidae of which *A. aequidens* belongs, describing distribution, habitat and general biology. Following this is a brief summary of global fisheries that target sciaenids. General information on age, growth and reproduction of sciaenids are then presented. Particular emphasis is given to: a.) other sciaenids found in Australia and, b.) like *A. aequidens*, species that are in the tribe Cynoscionini.

1.3 Introduction to Sciaenids

The family Sciaenidae (mulloway, croakers, drums) is a large, diverse group containing 291 species from 66 genera and is among the largest of families in the order Perciformes (Chao, 1986; Bortone, 2003; Froese and Pauly, 2011, Eschmeyer and Fong, 2013). They are a cosmopolitan family inhabiting coastal and estuarine waters of tropical to temperate areas of the Atlantic, Indian and Pacific Oceans, with a few species also occurring in fresh water habitats, mainly in South America (Steffe and Neira, 1998; Helfman *et al*., 2009). Many species in the family are commonly referred to as croakers and drums due to their ability to produce sounds using specialised swimbladders and muscles (Paxton and Eschmeyer, 1994; Helfman *et al*., 2009). In Australian waters, 20 species from nine genera have been recorded, however, *A. aequidens* (teraglin) and *A. japonicus* (mulloway) are the only two sciaenids found in the temperate waters of south-eastern Australia (Steffe and Neira, 1998; Hutchins and Swainston, 2006). *Argyrosomus japonicus* is a widely distributed sciaenid also found in South Africa, and is part of the biggest group of closely related sciaenid's, with 22 genera in the lineage (Lo *et al*., 2015).

Sciaenids have the most diverse morphologies of the percoids, which in itself is a distinct feature of the family. Body and mouth morphology are the two main features that differ widely enabling sciaenids to infiltrate a range of habitats (Chao and Musick, 1977; Sasaki, 1989). There is large variation in the maximum size of species with some only growing to 10 cm, such as species from the genus *Stellifer* (Nelson, 1994). Other species can attain very large lengths; the largest, the endangered *T. macdonaldi* found in the Gulf of California, Mexico, reaches a length of 200 cm. However, most species have a maximum size less than 40 cm (Paxton and Eschmeyer, 1994; Steffe and Neira, 1998). Colour is also highly variable and ranges from silvery tones to darker colours of brown or black, with juveniles of some species having spots and/or bands (Fisher and Bianchi, 1984; Sasaki, 2001).

Most sciaenids are marine, inhabiting sandy or muddy bottoms in coastal waters of the continental shelf between 20 and 200 m deep, estuaries and also rivers (Lo *et al*., 2015). A few genera occur in deep water (*Protosciaena bathytotos* to 600 m), surf zones (*Menticirrhus* spp.) and coral reefs (*Equetus* spp.) (Sasaki, 2001; Chao, 2002). The family is not found around oceanic islands of the Pacific and Indian Oceans (Sasaki, 2001; Ramcharitar *et al.*, 2006). They are commonly mid-water or bottom feeders, reflected in the anatomy of the mouth which is subterminal (mouth positioned ventrally from tip of snout) in mid-water feeders and inferior in bottom feeders. In addition, some species have one or more chin barbels that assist in the detection of prey on the ocean floor (Bortone, 2003; Allen *et al.*, 2006; Helfman *et al.*, 2009). Species mostly feed on small crustaceans, benthic organisms and fish. Teeth are mostly small with some species possessing large canines (Sasaki, 2001). They are typically solitary or found in scattered groups but some species form large spawning aggregations (e.g. *A. aequidens* off South Africa; Griffiths and Hecht, 1995a) that are targeted by commercial and recreational fisheries (Fisher *et al.*, 1981). Juveniles and young adults of many species are found in estuaries (Fisher *et al.*, 1981; Chao, 2002; Bortone, 2003).

Sciaenids are distinguishable from other perciform fishes by the deep notch separating spinous and soft rays on the long dorsal fin. The anal fin is comprised of 1-2 anal spines, in contrast to the three that are normally found in other Perciformes (Chao, 1986; Sasaki, 1989). They mainly have an elongated body shape and curved lateral line (Steffe and Neira, 1998). The lateral line is prominent and extends from the end of the caudal tail to the head where a series of pores on the snout and lower jaw exist (Sasaki, 1989). The extension of the lateral line supports the fact that sciaenids are particularly receptive to sound in their environment (Helfman *et al.*, 2009).

Sciaenids have extremely large otoliths, a common trait in sound producing fish, and many have a large tadpole shape sulcal groove on the sagittal otolith (Chao, 2002; Aguirre, 2003; Helfman *et al*., 2009). It is on the sulcal groove (located on the medial surface of the otolith) that the sensory tissues come into contact with the otolith (Aguirre, 2003). The ratios of the sulcus to medial surface of the otolith (S:O) in the sciaenid genus *Cynoscion* (Aguirre, 2003) are among the largest reported for any group of fish. Fish with a large S:O ratio may be more sensitive to sound, a particularly important feature for sciaenids as they are nocturnal and many are found in murky, turbid estuarine waters (Gauldie, 1988; Cruz and Lombarte, 2004). Being sensitive to sounds enables sciaenids to communicate with each other (e.g. during courtship), locate food items, and avoid potential predators (Monteiro *et al*., 2005). The swimbladder is thick walled and well developed enabling many species to generate the characteristic croaking and drumming sounds (Ramcharitar *et al*., 2006).

Otolith and swimbladder shape have been employed in systematics to classify species to genus and species level (Trewavas, 1977; Chao, 1986; Sasaki, 1989). Swimbladder morphology varies in shape and in the connecting appendages that are located anteriorly. Chao (1986) identified six basic forms, ranging from a primitive carrot shape with no appendages (*Sciaena*) to swimbladders with tubelike appendages in various patterns, either single or multiple branches extending along the length of the structure (*Pseudotolithus typus*). In some countries surrounding the Indian Ocean and western Central Pacific, the swimbladder from large sciaenids (e.g. *Cynoscion*) are dried and sold commercially for the manufacturing of isinglass (used in the wine industry) or as a food delicacy (Fisher and Bianchi, 1984; Chao, 2002). In numerous species (e.g. from the genera *Cynoscion*) the drumming and croaking sounds are only produced by males using well developed drumming muscles during courtship (Ramcharitar *et al*., 2006). Sound production is very diverse, with inter- and intra-species variation in frequency and number and duration of pulses and grunts (Bortone, 2003; Ramcharitar *et al*., 2006)

Based on swimbladder and otolith morphology, four genera make up a monophyletic tribe known as Cynoscionini (Chao, 1978 as sighted in Bortone, 2003; Sasaki, 1989). The tribe is recognised as including 31 species from the genera *Atractoscion* (2 species), *Cynoscion* (24 species), *Isopisthus* (2 species) and *Macrodon* (3 species) (Bortone, 2003). These genera are endemic to the tropical and warm temperate waters of the Americas in the Northern Hemisphere with the exception of *A. aequidens* (the subject of this research) found in the southern hemisphere off South Africa and Australia (Bortone, 2003). The common characteristics of the tribe are an elongated body and horn like appendages at the anterior end of the carrot-shaped swimbladder. There is some contention regarding the claim of a monophyletic tribe. A study (Vergara-Chen *et al.*, 2009) found that a species from the *Cynoscion* genera (*C. guatucupa*) is closely related to *A. nobilis* and should be included in the *Atractoscion* genus. Further studies on the phylogeny of the tribe are needed, in particular, species from the highly diverse *Cynoscion* genus.

In Australia, *A. aequidens* is distributed from Double Island Point in south-east Queensland (25.93°S, 153.18°E) to Montague Island in NSW (36.15°S, 150.13°E) (Steffe and Neira, 1998; Hutchins and Swainston, 2006). Unlike *A. japonicus,* the only other sciaenid found in NSW, the life cycle of *A. aequidens* is thought to be completely marine. In Australia, *A. aequidens* has been reported to reach a maximum length of 100 cm and weight of 9 kg (Hutchins and Swainston, 2006), remarkably smaller than the maximum length and weight of 130 cm total length (TL) and 25 kg, respectively, reported for *A. aequidens* in South Africa (Griffiths, 2000a).

A summary of maximum lengths and life history characteristics for several species from the Cynoscionini tribe and other important sciaenids is shown in Appendix A (pg. 107) and discussed in chapter 3 (Reproduction) and chapter 4 (Age and growth).

1.4 Reproduction

While sciaenids are diverse in morphology and habitat, they share the common reproductive traits of a protracted spring to summer spawning season, multiple batch spawning and nocturnal spawning periodicity (Holt *et al*., 1985; Waggy *et al*., 2006) (Appendix A). Large sciaenids (> 1 m in length) share additional reproductive behaviour such as formation of large spawning aggregations and use of estuaries as nursery grounds for larvae (Waggy *et al*., 2006). Three reproductive strategies occur among the sciaenids found off Central America in the Atlantic Ocean (Waggy *et al*., 2006). The first group of species is characterised by long life span (mean 28 yr), large maximum size (mean 1.3 m), large age (mean 4 yr) and length at maturity, low spawning frequency and relatively low fecundity. The second "intermediate" group has a shorter life span (mean 4 yr), small maximum size (mean 47 cm FL), small size and age at maturity (mean 4 yr), short spawning season, higher spawning frequency and relative high fecundity. The third group labelled "lesser" was based on only one species, with smaller characteristics to the other two groups (Waggy *et al.,* 2006).

Atractoscion aequidens in South Africa is typical of a large sciaenid. The only study completed on the reproductive strategies and spawning season of *A. aequidens* (Griffiths and Hecht, 1995a) found that 50% of fish matured at 90 cm FL and 5 yr, with 100% of fish being mature at 96 cm FL and 6 yr. Through analysis of commercial catch returns, it was found that the species consists of three sub-populations that undergo well defined migratory patterns (Griffiths and Hecht, 1995a; Hutton *et al*., 2001). This life history characteristic is thought to be due to the close predator-prey relationship with bait species providing energy for migration and reproductive spawning. The spawning season is protracted, occurring over spring and summer (Griffiths and Hecht, 1995a).

Atractoscion nobilis forms spawning aggregations over kelp beds near rocky headlands on a lunar cycle (Allen and Franklin, 1992; Aalbers, 2008). Commercial market sampling and occurrence of juvenile *A. nobilis* indicate a protracted spawning period during the northern hemisphere summer (Vojkovich and Reed, 1983; Donohoe, 1997). Sexual maturity is reached at 42 cm FL in males and 54 cm FL in females (Clark, 1930; Hervas *et al*., 2010). The length at which 100% of the *A. nobilis* population reaches sexual maturity is 80 cm TL and 6 yr (Clark, 1930; Thomas, 1968). The eggs of *A. nobilis* are the largest reported for any sciaenid species (1.2– 1.3 mm diameter) and are pelagic (Moser *et al*., 1983; Steffe and Neira, 1998). Eggs of *A. aequidens* are currently undescribed.

Due to the cosmopolitan distribution of sciaenids, many have intra-specific variations in reproductive traits such as size at maturity and duration and timing of the spawning season. For example, in NSW *A. japonicus* mature at a much younger age (2-3 yr) and smaller length (51-68cm TL) than in South Africa (5-6 yr, 92-107cm TL) (Appendix A). The study in NSW found that 50% of the female population reach maturity at 68 cm TL which is equivalent to 3 yr. Males matured at a smaller size of 51 cm TL and younger age, around 2 yr (Silberschneider and Gray, 2005). Based on macroscopic gonad staging, spawning appears to take place primarily between spring and summer but may vary between regions (Silberschneider and Gray, 2005).

The late onset of sexual maturity makes large sciaenids vulnerable to recruitment failures if large females are heavily targeted and removed from the population (Hutchings, 2000). Removing larger females may also result in a reduction in the size and age of onset of maturity, allowing the species to adapt to continuous and heavy fishing pressure (Law, 2007). This is of particular concern as studies on species from a range of families have shown that larvae produced from smaller, younger fish do not grow as fast or withstand starvation as well as larvae spawned from older, larger fish (Hutchings, 2000; Berkeley *et al*., 2004; Green, 2008). In addition, removal of larger females can impact on genetic diversity. *Argyrosomus japonicus*, dusky kob, in South Africa has experienced continual removal of larger, breeding fish over several decades. Genetic analysis indicates signals of a genetic bottleneck and the fishery has been in a state of collapse since the 1990s (Mirimin *et al.,* 2016).

1.5 Age and growth

Due to the fact that many of the larger sciaenids support significant fisheries, it is these species that tend to have the most age and growth data available (Waggy *et al*., 2006). Studies on larger sciaenids indicate that many can be long lived (42 years), mature late in life (6-9 years) and at large sizes (greater than 90 cm fork length, FL) (Griffiths and Hecht, 1995a, 1995b; Silberschneider *et al*., 2009) (Appendix A). The only comprehensive study on the life history characteristics of *A. aequidens* has been in South Africa, where they reach a maximum length of 130 cm TL and a maximum weight of 25 kg (Griffiths and Hecht, 1995a; Griffiths, 2000a). *Atractoscion aequidens* grew at a rapid rate, reaching approximately 40 cm FL at one year and 90 cm FL at five years of age. Growth slowed markedly at the onset of sexual maturity, with no difference in growth rates between sexes. The oldest age estimated was 9 years which is much younger than another important sciaenid found in South Africa, *A. japonicus* (known as dusky kob), which has been aged to 42 years (Griffiths and Hecht, 1995a, 1995b).

Despite the importance of *A. nobilis* in fisheries in the eastern Pacific Ocean off southern California, studies have been limited to the north and only recently have growth rates been examined across the species' range and over a range of sizes (Romo-Curiel *et al.,* 2015). In the North Pacific Ocean, *A. nobilis* were found to grow rapidly in the first 8 yr where growth subsequently slowed. The oldest fish sampled was 28 yr (Romo-Curiel *et al.,* 2015). Similar to other sciaenids (Griffiths and Hecht, 1995; Barbieri *et al.,* 1994) size-at-age was found to be highly variable, attributable to differing growth rates due to variations in water temperature (Williams *et al.,* 2007). The species has been recorded at a maximum length of 160 cm and weight of 40 kg (Donohoe, 1997). Maximum size and age are reported for numerous sciaenids in Appendix A (pg. 107).

Growth rates of *A. japonicus* in NSW and South Africa are similar, however, attains a much larger size and age in South Africa (181cm TL, 42 yr) than in NSW (132 cm TL, 24 yr) (Griffiths and Hecht, 1995b; Silberschneider *et al*., 2009). In the only comprehensive study into the life history characteristics of *A. japonicus* in NSW, growth was similar between males and females until females reached sexual maturity after which females grew faster and attained greater lengths (Silberschneider *et al.*, 2009).

1.6 Aims and objectives

It is clear from a review of the literature that species from the family Sciaenidae support many significant fisheries world-wide. However, information on important life history characteristics is limited to a relatively few number of sciaenids. This is a concern as global fishery landings decline, effort on fishing resources and the human population increase. Management of the planet's precious fisheries resources is as important as ever and the key to their effective management is knowledge of species' life history characteristics.

The aim of this study is to support sustainable management of the *A. aequidens* fishery in NSW by investigating relevant aspects of the species' life history and biology. To date, there has been no detailed study on the life history characteristics of *A. aequidens* in NSW. The existence of geographical and temporal variation in age, growth and reproductive characteristics will be investigated and compared with information available from southern Queensland and South Africa. Knowledge of a species' reproductive characteristics, and age and growth parameters, are paramount to ensure fishing mortality rates do not exceed the ability of a species to naturally replenish. Further, heavy exploitation of a stock can lead to decreased resilience to environmental changes therefore it is imperative to determine life history characteristics to ensure sustainability (Hsieh *et al.,* 2006).

Chapter 2: Description of Sciaenid and *Atractoscion aequidens* fisheries

Abstract

Species within the family Sciaenidae comprise one of the most important groups of fish, supporting many commercial and recreational fisheries throughout their global distribution. For many species, a lack of life history information during fishery exploitation, coupled with slow growth, late size and age maturity, and spawning aggregations, has meant many sciaenid stocks have become severely depleted. In South Africa, a state of emergency was declared in 2000 in response to the large declines in their line-fishery, including catch rates of two highly prized sciaenids *Argyrosomus japonicus* and *Atractoscion aequidens*. The same two species of sciaenid are found in the temperate waters off south-eastern Australia. Both have a long history of exploitation in NSW and while *A. japonicus* has been extensively studied and is assessed as overfished, the life history characteristics or fisheries of *A. aequidens* has never been studied. The aim of reviewing the fisheries data in NSW is to describe the development and history of the fishery to provide information to assess the status of the stock. The commercial fishery for *A. aequidens* in NSW has been in existence for more than 60 years. The fishery reached a high of approximately 200 t per annum in the 1950s and has declined ever since, with recent landings of 30 t per annum. There has also been a geographical shift in commercial landings, from Sydney (which was the major port of landings during the development of the fishery), to the more northern ports of Forster and Coffs Harbour. The long-term decline in landings in NSW, combined with the indications from stocks of the same species overseas, suggest that the species is susceptible to high exploitation. The most recent determination of the stock status of *A. aequidens* in NSW is uncertain due to lack of life history and fishery information and it is hoped that the current study will result in the status of the commercial fishery in NSW to be better understood.

2.1 Global fisheries

Many sciaenids support significant recreational and commercial fisheries world-wide such as drummer (*Sciaenops*), weakfish and sea trout (*Cynoscion*) and kingfish (*Menticirrhus)* in the Americas; croakers (*Larimichthys* and *Pennahia*) in Asia and mulloway (*Argyrosomus*) in Africa and Australia (Helfman *et al*., 2009; FAO, 2011). Numerous species also support aquaculture industries and are used in wild fish stock enhancement programs (Silberschneider and Gray, 2005). Sciaenids are popular due to the high quality of their flesh, (including the swimbladder which is considered a delicacy in some countries) and their fighting ability, a quality which makes them a prize target among recreational anglers (e.g. species from genera *Argyrosomus, Cynoscion* and *Atractoscion*) (Bortone, 2003; Hutchins and Swainston, 2006).

In the FAO Yearbook of Fishery Statistics report for 2014 (FAO, 2014), a total of 1,754,434 t of sciaenids was reported landed world-wide. Of that, the northwest Pacific off East Asia, had the greatest total landings of 973,017 t, almost half of which are landings of *Larimichthys polyactis*, a relatively small sciaenid growing to a maximum length of 40 cm. Large quantities are also landed in the western and eastern Indian Ocean however no species-specific information on landings is available. Reconstructed global fishery data estimate the true landings to be as much as 50% higher than reported to the FAO, with possible declines of three times that apparent from FAO landings (Pauly and Zeller, 2016). The total catches reported for sciaenid species may be higher than those stated above due to the published landings data covering only a few selected species and data from some countries being estimated, unavailable or incomplete (Gonzalez-Quiros *et al*., 2011).

In many fisheries, sciaenids are targeted commercially using bottom-trawl gear and bottom-set gill nets (Chao, 2002). Juveniles of many sciaenid species make up a large proportion of by-catch in prawn trawlers (Chao and Musick, 1977; Waggy *et al*., 2006; Silberschneider and Gray, 2008). Recreational fisheries land many sciaenid species using handlines and rods, which are also employed in certain commercial fisheries such as those targeting *A. japonicus* and *A. aequidens* in Australia and South Africa.

While large fisheries exist for smaller, fast growing sciaenids, many fisheries are based on larger fish that have slow growth rates and late onset of sexual maturity. These characteristics make them vulnerable to overfishing and many species have shown significant declines during the last few decades (Sadovy and Cheung, 2003). The large, slow growing sciaenid *T. macdonaldi* was one of the first marine fish to be classified as endangered under threatened species legislation (Chao, 2002).

Many species within the Cynoscionini tribe support large fisheries, among the most important for many countries. In the USA and South America the majority of sciaenids landed are from the genus *Cynoscion* (Bortone, 2003). While there are 24 species in the genus, biological information to underpin fisheries management is available for only two species (*C. nebulous* and *C. regalis*). Both species are extremely popular among recreational fishers and funding for research is therefore available (Bortone, 2003).

Long-term declines have occurred for the congeneric *A. nobilis,* which is the largest sciaenid found off southern California and was once a highly significant species in the region (Donohoe, 1997). *Atractoscion nobilis* is the only other species found in the *Atractoscion* genus, and shares many similarities to *A. aequidens* in South Africa, such as migratory spawning aggregations and late onset of sexual maturity (Griffiths and Hecht, 1995a). Spawning aggregations occur at rocky headlands and kelp beds, and heavy fishing pressure has resulted in a possible range contraction for the species (Vojkovich and Reed, 1983; Donohoe, 1997; Pondella and Allen, 2008). However since the implementation of a ban on gill netting in the commercial fishery off California in 1994, the stock of *A. nobilis* appears to be recovering with commercial catch levels comparable to landings prior to the collapse of the fishery (Allen *et al*., 2007; Erisman *et al*., 2010). However, recreational landings have not recovered to historical levels (Hervas *et al*., 2010).

2.2 South African fisheries

In South Africa, *A. aequidens* is a premier line-caught species in both the commercial and recreational fisheries. The species has a long history of decline in both fisheries, where it is targeted throughout its 2000 km distribution (Griffiths and Hecht, 1995a; Hutton *et al*., 2001). Poor management of the fishery and the well-defined migratory formation of large spawning aggregations in early summer and late onset of sexual maturity, led to the demise of the stock in South Africa (Griffiths, 2000). Average catch per unit effort (CPUE) has dropped to less than 5% of historical levels (Griffiths, 2000b) due to inadequate management stemming largely from a lack of life history information (Griffiths, 20000; Sadovy & Cheung, 2003). Referred to as ‘geelbek’ in reference to the unique yellow mouth, *A. aequidens* has had a long history of commercial and recreational importance since the fishery started in the early 19th century (Griffiths, 2000). In the early 1900s the species dominated landings and in three of the four Cape regions was the primary target species (Mann, 2000). The South African line-fishery, known as the “Cape” fishery, had a total of 2,500 licensed fishing vessels landing approximately 15,500 t of fish (Griffiths, 2000); however there has been significant declines in landings since this time. The South African government declared a state of emergency on the line fishery in the late 1990s with the two sciaenids targeted, *A. aequidens* and *A. japonicus,* suffering heavy depletion (Blamey *et al*., 2015). The decline of *A. aequidens* in the South African line-fishery has been dramatic with a drop in CPUE of 96-98% of historic levels and the stock is severely depleted (Griffiths, 2000; Hutton, *et. al*, 2001). Following the state of emergency on the line-fishery, a 70% reduction in effort was enforced; however, the current status of most line fish in South Africa is collapsed or unknown. In a study looking at declines in fish biomass in South Africa in relation to the southern Benguela current, a significant decline in biomass was evident from 1997-2000 and a further decline occurred between 2003-2008 (Blamey *et al.,* 2015). Even with reductions in effort, the pressure on the line-fishery is still relatively high given such low abundance of the targeted sciaenids (Blamey *et al.,* 2015). While a reduction of 70% in commercial fishing effort was implemented to assist in rebuilding stock abundance, the majority of the commercial fishing vessels in the fishery are the same vessels that landed the majority of historic landings (DAFF, 2014).

2.3 Queensland fishery

In QLD, *A. aequidens* is a key secondary target species of the commercial and recreational Rocky Reef Fin Fish Fishery (RRFFF). The commercial fishery is opportunistic with variable landings (QLD Fisheries, 2010). As of 2010, the fishery comprised 1,315 commercial licenses with 347 accessing the fishery and landing 229 t of fish, including 15 t of *A. aequidens* (QLD Fisheries, 2010). In the QLD fishery, *A. aequidens* is more significant in the recreational and charter boat fishery (QLD Fisheries, 2010). Between 2008 and 2009 there was an increase in landings of 44% in the QLD charter boat fishery to 23 t (QLD Fisheries, 2010). The species' exploitation status is currently listed as 'uncertain' and it is the subject of biological and length frequency monitoring for both the commercial and recreational fisheries (QLD Fisheries, 2010). Management regulations in QLD include a bag limit of 5 fish per person per day for recreational anglers and a minimum legal length of 38 cm TL in both fisheries. In both fisheries, *A. aequidens* is landed by linefishing (rods and handlines) and is often targeted close to the full moon (pers. comm. Nick Clarke, recreational fisher).

2.4 NSW recreational fishery

Recreational anglers target the species over similar grounds to that of the commercial fishery with handlines and target the species due to the voracious feeding behaviour and fine quality flesh. The recreational catch of *A. aequidens* in NSW was originally estimated to be significantly larger than the commercial harvest, as is the case for many sciaenids world-wide (Henry and Lyle, 2003; Silberschneider *et al.*, 2009; Ferguson and Ward, 2011; Gonzalez-Quiros *et al.*, 2011). However original estimates were pooled with the other sciaenid in NSW, *A. japonicus,* which grow to a much larger size than *A. aequidens* (Silberschneider and Gray, 2005). The estimated recreational harvest was between 70-110 t (Rowling *et al.,* 2010) and is now believed to be inflated. In a recent estimate of recreational harvest from a state-wide survey in NSW (West *et al.,* 2015), the estimate was 33, 000 fish, similar to the previous estimate of 38,000 fish in 2003 (Henry and Lyle, 2003). This was calculated to be in the order of 37 t, similar to current commercial landings (Stewart *et al.,* 2015). There are however anecdotal reports of a significant decline in the recreational fishery, similar to that of the commercial fishery, having occurred off NSW. While there are no quantified estimates of historical recreational estimates prior to the expansion of the fisheries, *A. aequidens* was once prolific off the coast of Sydney (1970s) and targeted heavily by recreational fishers and is no longer landed in similar quantities (pers comm K. Rowling). The minimum legal length in both fisheries is 38 cm TL and for recreational anglers there is a bag limit of 5 fish per angler.

2.5 NSW commercial fishery

Atractoscion aequidens has a long history of being targeted by the commercial fishing sector in NSW (Stewart *et al.,* 2015) principally within the Ocean Trap and Line Fishery (OTLF), one of eight fisheries operating in NSW. The OTLF is a multi-species and multi-gear fishery and in 2014/15 produced approximately 1,374 t of seafood valued at $19 million (NSW Primary Industries commercial catch records). It is managed by the NSW state Government and extends to 80 nautical miles from the coast. Fishers target *A. aequidens* predominantly by handline whereby single lines with hooks or gangs of hooks are deployed over gravel or broken reef at depths between 10 and 80 m. The boats employed in the OTL fishery are mostly 6-8 metres in length (FMS OTL, 2006).

The goals of the OTLF Fishery Management Strategy (2003) include: 1) managing fisheries that promote conservation, and; 2) maintaining stocks of primary and key secondary species harvested by the OTLF at sustainable levels. Central to these two aims is knowledge of the life history characteristics and fishery information for exploited species. *Atractoscion aequidens* is classified as a key secondary species which is defined as a species other than the primary target that is an expected catch and retained for subsequent sale (OTLF FMS, 2006).

In 2015, the state fisheries agency, NSW Primary Industries, classified the stock of *A. aequidens* as “uncertain” (Stewart *et al.*, 2015). This classification was based on preliminary examination of commercial catch history and rates, length frequency and age composition analysis of a representative sample of the fishery.

Argyrosomus japonicus is also targeted in the commercial and recreational fisheries in South Australia, Western Australia, Victoria, and QLD. Throughout its Australian distribution there are concerns that *A. japonicus* is overfished (Farmer *et al*., 2005; Silberschneider *et al*., 2009; Stewart *et al*., 2015; Ferguson and Ward, 2011). Long-term declines in commercial landings and the highly sought after nature of the species among recreational fishers have heightened concern for the status of the stock (Silberschneider and Gray, 2005). While no time series exists for estimates of recreational landings, estimates from a single national recreational survey indicated catches of *A. japonicus* were much greater than the commercial harvest in each jurisdiction (Henry and Lyle, 2003; Silberschneider *et al*., 2009). A long-term decline in the mean size of landed fish, and the fact that current landings are almost entirely based on juveniles, indicate a heavily exploited population (Silberschneider & Gray, 2005).

2.5.1 Landings

Commercial fishers are required by law to record and submit effort and catch information of their fishing activities. Since exploitation of *A. aequidens* commenced in the 1940s there have been three different commercial catch logbook systems. These systems cover the periods 1947/48 to 1983/84, 1984/85 to 2008/09 and 2009/10 to present time. The latest commercial logbook system requires fishers to complete catch information on daily catch and effort for species landed (http://www.dpi.nsw.gov.au/fishing/commercial/catch-effort). Reported commercial landings of *A. aequidens* in NSW are available back to 1947/48 (Figure 2.1.) and range from a peak of over 200 t in 1956/57 to a low of 7 t in 2005/06. Overall landings have been declining since the early years of the fishery and over the last 10 years have remained low, on average below 30 t, with evidence of peaks and troughs overtime. Between 1947/48 and 1979/80, the largest peak in the fishery of over 200 t was followed by a drop of more than 50% the following year. During the following 7 years, landings remained relatively stable below 100 t. In 1965/67 this increased to

175 t, then declined to 100 t in 1966/67 and dropped to 50 t in 1968/69. In the early 1980s, landings averaged more than 40 t, however landings dropped by 50% in 1986/87. Following a few years at approximately 20 t, the fishery increased to a high of 50 t in 1992/93 followed by another large drop in total landings. The last 5 years has seen the fishery averaged below 30 t. Despite the presence of sporadic increased landings, the overall trend is one of decline.

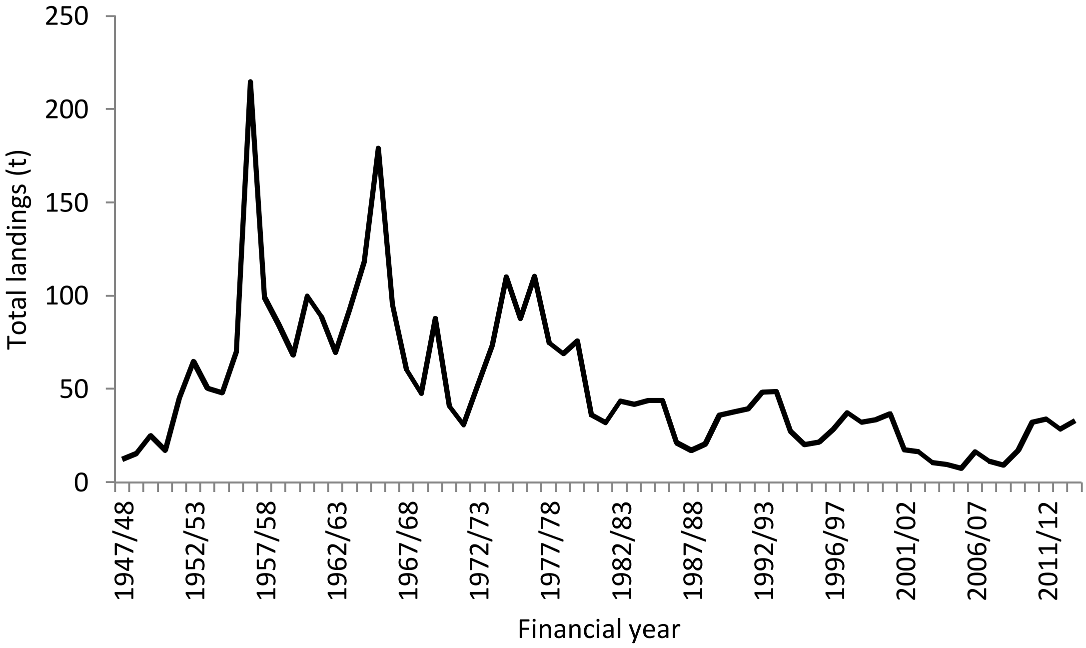


Figure 2.1. Total commercial catch landings in NSW for *Atractoscion aequidens* from 1947/48 to 2013/14. Source Fisheries NSW commercial database.

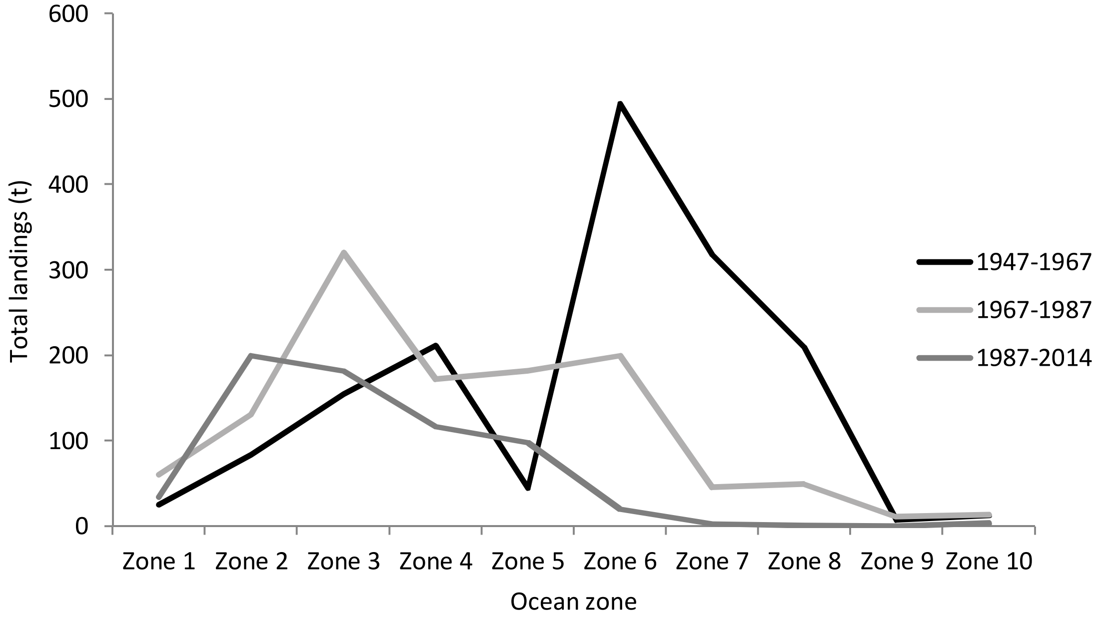


Figure 2.2. Percentage of catch in NSW for *Atractoscion aequidens* by zone pooled periods 1947-1967, 1967-1987 and 1987-2014. Source Fisheries NSW commercial database.

As there has been large variability in the total landings of *A. aequidens* throughout the history of the fishery, total landings were pooled into three 20 year periods to observe any changes in distribution of landings by ocean zone (Figure 2.2.). The OTL fishery in NSW is divided and operated by fishing zones, each based on 1° of latitude, giving a total of 10 spanning the coast (Figure 2.3.). There is evidence of a shift in the main commercial fishery from the more southern part (zones 6-8) of the range to the more northern part (zones 2-5) of the range. In the most recent period, virtually no commercial fishery of *A. aequidens* exists in zones 6 and 7 when previously was a major region of commercial landings. During the 20 year period 1947-1967, landings from these two zones accounted for over 60% of the total catch. In the most recent 20 year period, this level is substantially smaller, less than 5% of the total catch. Zone 2, made up 30% of the catch landings in 1987-2009, only contributed 5% of landings in 1947-1967. Landings in the southern zone 9 and 10 have always been low in the history of the fishery. Further research with detailed analysis of catch rates within the handline commercial fishery would assist in a better understanding of the possible drivers of the range shift.

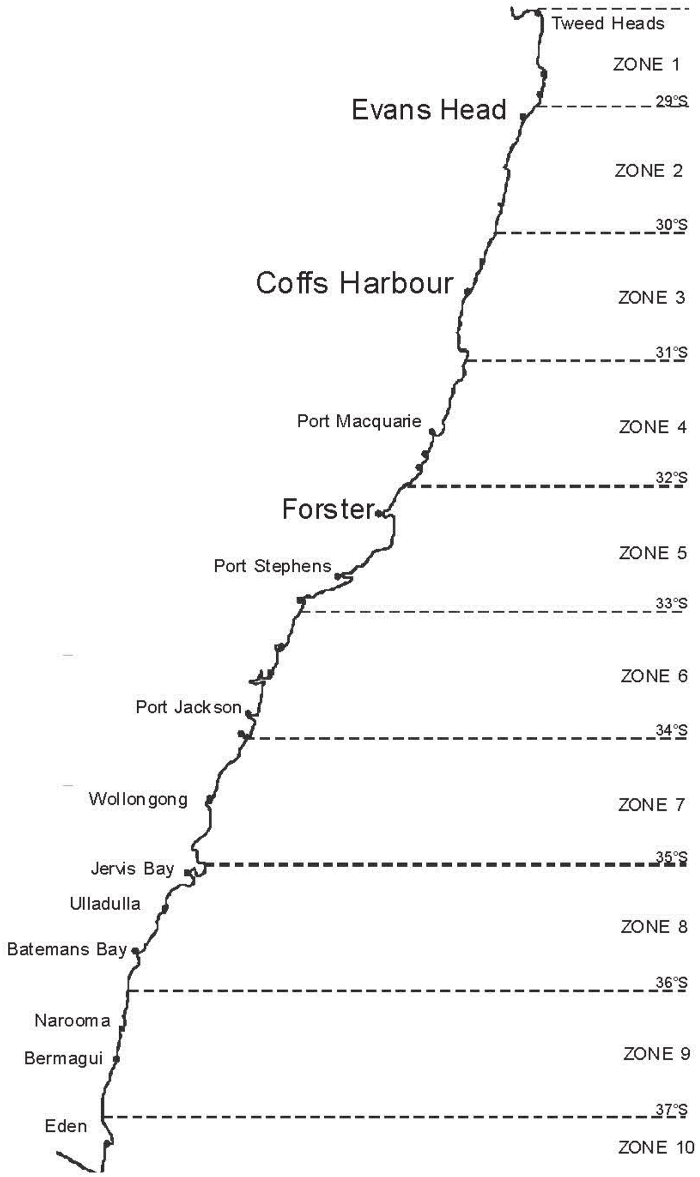


Figure 2.3. Ocean zones in the Ocean Trap and Line Fishery for reporting commercial landings in NSW.

2.5.2 Length frequency distributions

Commercial length frequency data exists back to the 1970s and comprised mainly of fish 40-65 cm FL with a high proportion 50-65 cm FL (Figure 2.4.). Length data from the early mid to late 2000s comprised of fish between 40-50 cm with very few over 55 cm FL. The most recent period of data contains fish mainly 37-53 cm FL, and only a small proportion of fish greater than 55 cm.

The length frequency distribution of the landed catch from the commercial fishery indicated a higher proportion of smaller fish being caught from 2004 to 2009 compared to the distribution in the 70s and early 2000s. The recent distribution between 2010 and 2014 indicates a very slight increase in the proportion of larger fish between 50 cm-54 cm FL. For all graphs presented there is a very low proportion of fish over 65cm FL which is of interest considering the species is said to grow to a maximum of 100 cm FL (Hutchins & Swainston, 2006). The fact that there is little difference in the proportion of larger fish (> 65 cm FL) when comparing distributions from the 1970s to recent monitoring data, suggests the species may already have been fished down to a low level before the 1970s. This is further shown in the commercial landings data with landings very low and a possible geographically shift with virtually no landings of *A. aequidens* off Sydney and Wollongong anymore.

The recent higher proportion of smaller fish and low proportion of larger fish in the recent length frequency data may be due to the removal of larger fish through fishing. It should be noted that the fishing down of the larger fish may have occurred prior to the collection of any size composition data in the 1950s and 1960s. An alternative hypothesis is that there have been recent increases in recruitment of small fish to the fishery; however this does not explain the absence of very large fish.

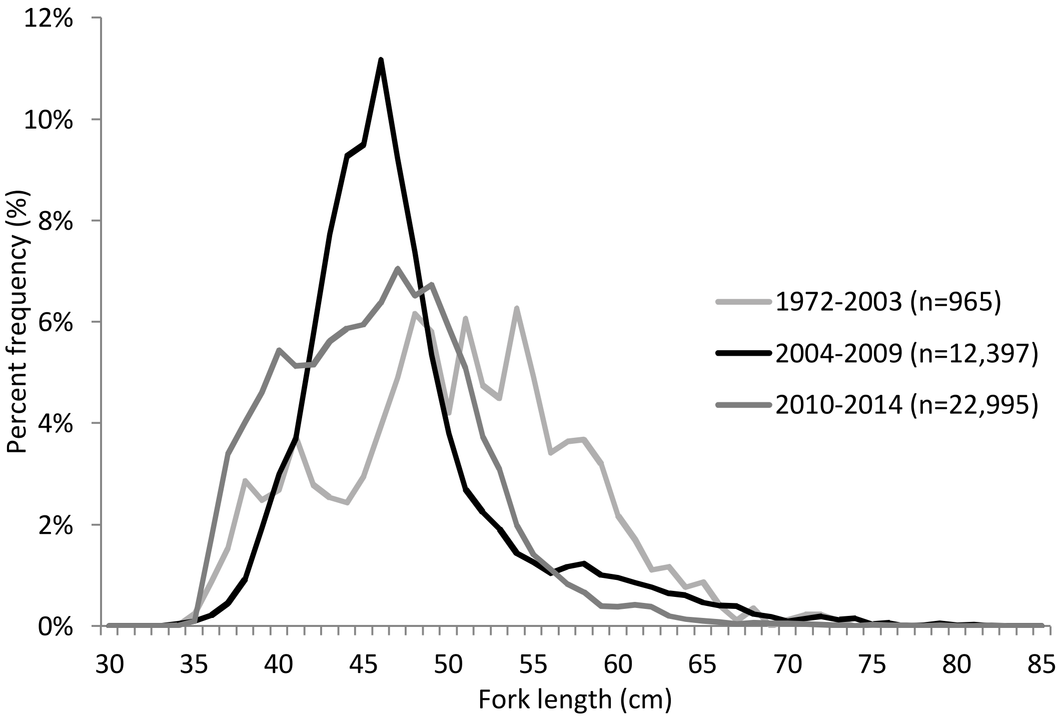


Figure 2.4. Commercial fishery length frequency distributions for *Atractoscion aequidens* in NSW by pooled by periods 1972-2003, 2004-2009 and 2010-2014. n values indicated on graph.

2.6 Further research

More detailed analysis of these statistics in terms of standardised catch per unit effort would allow a better understanding of changes in the abundance of the stock. These results would underpin the development of a quantitative population model, allowing an assessment of changes in the spawning biomass of *A. aequidens* over time.

2.7 Conclusion

Long-term monitoring data is paramount to the effective assessment of fish species so stocks can be fished at sustainable rates (OTLF FMS, 2006). Without estimates of catch rates and catch composition data, it is extremely difficult to determine what levels to compare current data with. As discussed by Griffiths (2000), poor management of *A. aequidens* in South Africa was exacerbated by “shifting base-line syndrome” (Pauly, 1995), which was caused by each new generation of scientists and mangers disregarding previous estimates of abundance as unsubstantiated anecdotal reports. Without long-term monitoring data, the management of *A. aequidens* in South Africa, and the case for many other species worldwide, was based on the species' perceived vulnerability to fishing (Griffiths, 2000). Historical catch data is extremely important in order to assess the impacts of fishing on a species and to rebuild any depleted stocks.

There are concerns the *A. aequidens* stock in NSW is also depleted, with the current status of the fishery uncertain due to lack of life history information. The commercial fishery is well below landings seen in the past (Stewart *et al.,* 2015) and there is evidence of changes in range distribution. It is crucial that the status of the stock be accurately determined based on the life history of the species to equip the management of the species.

Chapter 3: Reproductive biology of *Atractoscion aequidens* in New South Wales, Australia.

Abstract

Teraglin (*Atractoscion aequidens*, family Sciaenidae) is found in eastern Australian waters from southern Queensland (QLD) to Montague Island in southern New South Wales (NSW). Despite a long history of fishery exploitation, there has been no detailed study of the life history characteristics and population dynamics of the species in NSW. The aim of this study was to describe the reproductive characteristics including size and age at maturity, fecundity, spawning mode and season in NSW and compare to populations in southern QLD and Africa. In NSW, *A. aequidens* is an asynchronous batch spawner with indeterminate spawning (the standing stock of oocytes does not give an indication of annual fecundity). Batch fecundity estimates ranged from 32,431 (± 2,370) for a 43 cm fish to 673,813 (± 2,929) for a 71.5 cm fish. Monthly gonadosomatic index values averaged over the sampling period January 2011 to June 2012 indicate reproductive activity for most of the year for both sexes. Macroscopic and microscopic staging of gonads validated the occurrence of year-round spawning. This is unusual for sciaenids, which typically display spring-summer spawning over a short 3-month period. The length and age at which 50% of the population matures for both males and females is 36 cm fork length (FL) and 1 year. Results were similar to those found in QLD and Angola, but in South Africa, the same species matures much larger and older at 90 cm FL and 5 years. Knowledge of a species' reproductive characteristics underpins the development of management strategies and assessing a species' resilience to fishing and other sources of mortality.

3.1 Introduction

There is pressure on fisheries worldwide with many stocks over exploited and negatively affected by human-induced environmental stressors (Winemiller and Rose, 1992; Winemiller, 2005; Hsieh *et al.*, 2010). Knowledge of a species' reproductive characteristics including size and age at maturity, fecundity, spawning season, spawning frequency and growth rates are vital for the development of management strategies and assessing a species' resilience to fishing and other sources of mortality (Clardy *et al*., 2014). Furthermore, this information can be used to understand life history, recruitment and population dynamics of a species (Schaefer, 1987; Begg, 1998; Jakobsen *et al*., 2009). Importantly, previous notions of resilience to fishing pressure due to high fecundity and wide distributions are being proven incorrect with the collapse of fisheries based on relatively fecund species and recruitment success based on environmental factors more so than reproductive attributes (Pauly *et al*., 2002; Le Bris *et al*., 2015).

Atractoscion aequidens (Cuvier, 1830), (family Sciaenidae), known as teraglin, occurs in Australia from Double Island Point (25.93°S, 153.18°E) in south-east Queensland (QLD) to Montague Island (36.15°S, 150.13°E) on the south coast of New South Wales (NSW) (Steffe and Neira, 1998; Hutchins and Swainston, 2006). Known as geelbeck, it is also reported from South Africa (Griffiths and Hect, 1995) and Angola (Henriques *et al*., 2014). The species inhabits the waters of the continental shelf in depths of 20-80 m over gravel or broken reef (Stewart *et al.,* 2015). *Atractoscion aequidens* has been reported to reach a maximum length of 100 cm total length (TL) and maximum weight of 9 kg (Hutchins and Swainston, 2006), remarkably less than the maximum TL and weight of 130 cm and 25 kg respectively, reported for *A. aequidens* in South Africa (Griffiths, 2000a). The only other species in the *Atractoscion* genus, the white seabass, *A. nobilis*, is the largest sciaenid found off southern California and was once a highly significant species in the region (Donohoe, 1997). *Atractoscion nobilis* shares many similarities to *A. aequidens* in South Africa, such as migratory spawning aggregations and late onset of sexual maturity (Griffiths and Hecht, 1995a).

In NSW, *A. aequidens* is targeted by recreational and commercial fisheries (Stewart *et al*., 2015). The recreational catch of *A. aequidens* is estimated to be larger than the commercial harvest, as is the case for many sciaenids world-wide (Henry and Lyle, 2003; Silberschneider *et al*., 2009; Ferguson and Ward, 2011; Gonzalez-Quiros *et al*., 2011; Stewart *et al.,* 2015). In both fisheries, *A. aequidens* is caught by line-fishing (rods and handlines) and is often targeted around the time of the full moon. In NSW, large commercial landings were made in the mid-1950s when annual landings peaked at over 200 t, however in recent years landings have fallen to less than 30 t per annum (Stewart *et al.,* 2015). In NSW, the recreational catch in the early 2000's was estimated at approximately 37 t (Henry and Lyle, 2003) and a similar estimate was found in the most recent state-wide recreational harvest estimate (West *et al.,* 2015). There are concerns that the stock may be depleted with anecdotal evidence suggesting the schooling and voracious feeding behaviour of *A. aequidens* results in a high proportion of fish in a school being caught, thus making the species susceptible to overfishing (Sumpton *et al.,* 2013; Stewart *et al.,* 2015).

The areas covered by this study correspond to two distinct regions of the western boundary current, the East Australian Current (EAC), a poleward flowing current of the South Pacific Subtropical Gyre (Ridge and Dunn, 2003). The most northern sampling site (Evans Head) is influenced by warmer and nutrient poor waters from the Coral Sea. Coffs Harbour sampling site is located near Smokey Cape (30.90° S, 150.10° E), where the current strengthens (Suthers *et al*., 2011). In contrast, Forster is dominated by the highly variable separation zone of the EAC, where the main jet of the EAC detaches seasonally from the coast (Godfrey *et al*., 1980; Ridgway and Dunn, 2003; Suthers *et al*., 2011). Ocean temperatures and food availability are known factors affecting fish development and differences between the two regions will be investigated to determine any effect on fish reproduction.

Despite the relatively long history of exploitation, and the declining catches, there has been no previous study of the life history of *A. aequidens* in NSW. The current commercial fishery exploitation status of the species is "uncertain" (Stewart *et al.,* 2015) due to a lack of biological information and concerns of a depleted stock and possible overfishing. Therefore, the aims of the current study included addressing this knowledge gap by describing the reproductive characteristics of *A. aequidens* off the coast of NSW, including spawning period and strategy, oocyte development, fecundity, and size and age at maturity. Geographic and temporal variation in these parameters is analysed and compared between the south and north regions and by comparing the results of this study with information available from southern QLD and South Africa. The results of the study will provide information necessary for the assessment of the status of the stock to support the long-term management of the fishery.

3.2 Methods and Materials

3.2.1 Sample collection and study sites

Between January 2011 and June 2012, fishery-dependant biological samples were collected on a monthly basis from fishermen's co-operatives along the NSW coast. Samples were collected from three sampling sites, corresponding to major ports of commercial landings for *A. aequidens*: Evans Head (29.12° S, 153.43° E), Coffs Harbour (30.30° S, 153.12° E) and Forster (32.18° S, 152.51° E) (Figure 3.1.).

Ten fish were randomly selected each month from commercial landings for biological data collection from Evans Head (north area), Coffs Harbour (north area) and Forster (south area) fishermen's co-operatives. Biological data recorded for each sampled fish included fork length FL (±0.1 cm), body weight (±1 g), sex, gonad weight (±0.1 g), and gonad stage (see next section). Both sagittal otoliths were removed, cleaned, dried and placed in paper envelopes for storage. Some sporadic samples (n=94) were collected from commercial catches of *A. aequidens* at the Sydney Fish Markets during the study period from both the north and south regions. Samples collected during a pilot monitoring study on *A. aequidens* from Forster in 2006-2009 (n=330) were also included in the study. A total of 482 fish were collected from the north and 896 from the south.

To ensure the greatest possible length range of *A. aequidens* was sampled, specimens smaller than the minimum legal length (MLL, 38 cm TL) were collected from trawl catches off Forster and by handline off Iluka (just south of Evans Head; Figure 3.1.) by means of scientific collection permits.

In addition to the biological sampling, data on the length frequency distributions of commercial catches was also collected at the same three fishermen's co-operatives and at the Sydney Fish Markets as part of a NSW-wide fishery-dependent sampling program by Fisheries NSW. To sample recreational catches of *A. aequidens* fish frames were obtained from fishers in Sydney and at fishing competitions in Evans Head (FL, otoliths and sex only).

A Kolmogorov-Smirnov test was used to test the null hypothesis of no difference in the length-frequency distributions of males and females in the north and south areas. A chi-squared test was used to test the null hypothesis that male-female sex ratio did not differ from 1:1 and between the north and south areas. All analyses were completed using IBM SPSS Statistics for Windows (Version 22.0).

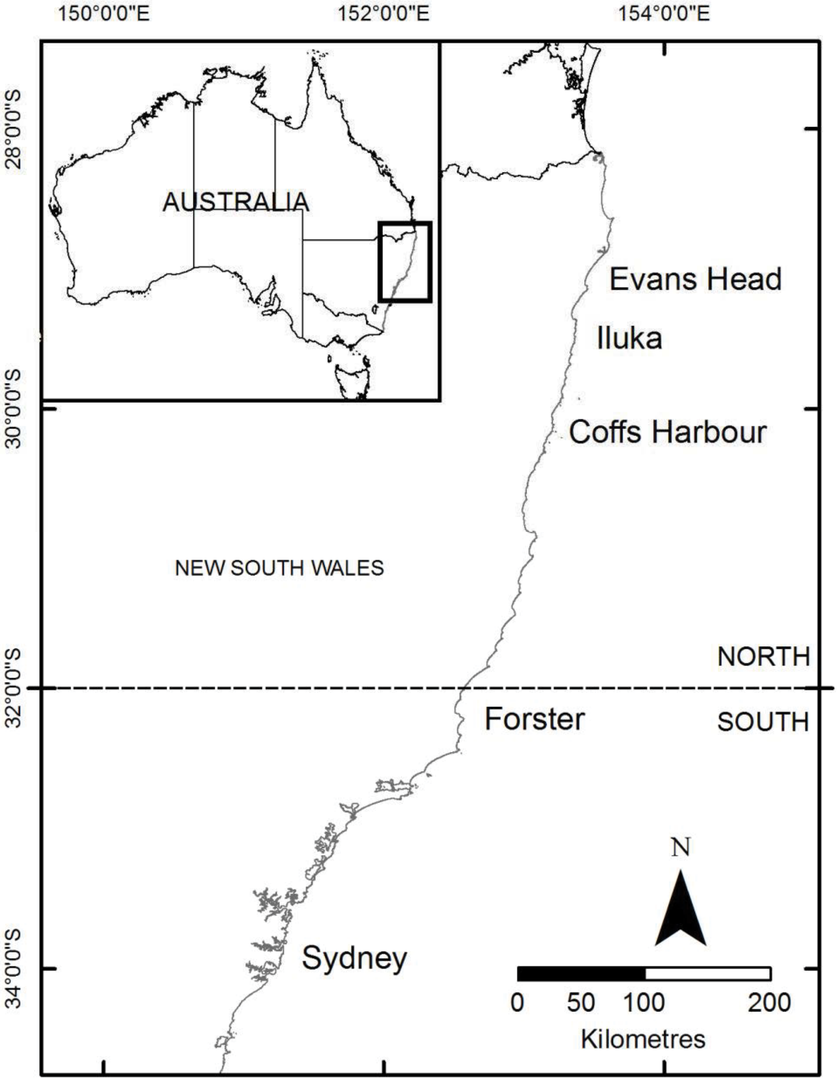


Figure 3.1. Map of NSW coast showing the locations of sites where *Atractoscion aequidens* was sampled. Dashed line indicates the separation of north and south regions (see text for explanation).

3.2.2 Macroscopic staging and gonad histology

Gonads were assigned to a gonad stage (Table 3.1., images in Appendix B) based on macroscopic appearance. Representative gonads from both males and females from a range of lengths, stages and sampling sites, were kept in a fixative solution of 10% formaldehyde, 5% glacial acetic acid, 1% anhydrous calcium chloride and 84% water (FAACC) for histology, fecundity estimates and oocyte size distributions. After two weeks the gonad samples were transferred into ethanol for storage.

Traditional methods of assessing reproductive activity based on macroscopic staging alone may overestimate the occurrence of spawning activity, and spawning strategy descriptions are more accurate after histological analysis (West, 1990; Lowerre-Barbieri *et al.*, 2009; Alejo-Plata *et al.*, 2011). Therefore, histology was completed on a sub-sample of 5 gonads from each gonad stage to validate the macroscopic staging. The fixed gonad tissue was embedded in paraffin wax and a 5 µm cross-section taken through the middle of the gonad and stained with haematoxylin and eosin. Histological sections were examined under a compound microscope and a microscope mounted camera (Q145 Imaging, MicroPublisher 5.0 RTV, Canada) was used to collect images of each gonad stage. Microscopic staging criteria for each stage are detailed in table 3.1.

Gonadosomatic Index (GSI) was calculated from the following equation:

$GSI=[Wg / (Ww - Wg)] \times 100$,

where Wg is gonad weight (g), and Ww is whole fish weight (g).

GSI was pooled separately for both mature (greater than stage 2) females and males (Figure 3.3.). Only fish that were over 35 cm FL were included in the macroscopic staging results to reduce bias due to immature fish. Due to higher sex ratio of females to males and difficulty in determining male macroscopic staging, the male gonad staging was not further analysed.

Table 3.1. Macroscopic and microscopic features of male and female gonads of *Atractoscion aequidens*. Images of macroscopic appearance of gonad stages in Appendix B.

Female		
Stage	Macroscopic Features	Microscopic Features
1. Immature	Determination of sex difficult. Ovaries tube like and very thin	Previtellogenic oocytes - perinucleolar and chromatin nucleolar
2. Developing/ Resting	Ovaries thin, yellow-orange in colour and jelly-like. No oocytes visible in ovary	Predominantly primary growth oocytes with larger primary cortical alveolar oocytes developing
3. Ripe	Ovaries yellow-orange colour with extensive vascularisation of ovary wall. Ovaries take up a large area of body cavity. Vitellogenic oocytes visible through ovary wall. No hydrated eggs visible	Mainly yolk granules are present (vitellogenic oocytes) due to cortical alveoli formation. Smaller previtellogenic oocytes also present
4. Running ripe	Hydrated eggs evident through ovary wall amongst vitellogenic oocytes. When gentle pressure is applied to abdomen, ova shed from genital pore. Ovaries are very large, occupying most of body cavity	Presence of hydrated oocytes and vitellogenic yolk granule oocytes. Previtellogenic oocytes also present
5. Spent	Orange-red in colour, bloodshot towards posterior end of ovary. Ovary sack like and loose, rubbery texture	Similar microscopic appearance to stage 2 (developing/resting) however may contain remanent yolk granule oocytes undergoing atresia
Male		
Stage	Macroscopic Features	Microscopic Features
1. Immature	Determination of sex difficult. Testes are thin and flat like	Mainly consists of primary and secondary spermatogonia
2. Developing/ Resting	Brown-cream in colour. Tough and rubbery feel. Do not take up much of body cavity	Early spermatids are present and spermatocytes
3. Ripe	Much larger in size, pinkish-cream in colour and easily ruptured. Do not expel milt when pressure exerted.	Spermatozoa present in sperm duct and seminiferous tubules. Also within lobules are spermatids and spermatocytes
4. Running ripe	Take up much more room in body cavity. Easily ruptured, milt expelled when pressure applied	Increase in occurrence of spermatozoa in seminiferous tubules and sperm duct
5. Spent	Similar appearance to stage 2. Testes brownish-white in colour and may be bloodshot at posterior end. Small amount of residual milt	Only residual spermatocytes present within testes, with minimal spermatids

3.2.3 Maturity

Maturity was based on macroscopic staging of gonads (criteria in Table 3.1., images in Appendix B) and categorized into either immature (Stages 1 and 2) or mature (Stages 3, 4 and 5). FL was used to determine length at maturity. Age at maturity was based on counts of annuli of sagittal otoliths (see Chapter 4).

The length and age at 50% maturity were calculated by determining the proportion of mature fish in 1 cm FL classes and 1 yr age classes. Attempts were made to compare maturity by north and south regions, however this could not be done for the north due to a lack of smaller (below the MLL) individuals and overall lower number of samples. Therefore, the data were pooled for all males and all females collected during the study and a logistic curve fitted to the pooled data for each sex (Chen and Paloheimo, 1994). The logistic curve was fitted to the data using Microsoft Excel and maximising log likelihood. The logistic curves for maturity for each sex were compared using the bivariate form of Wald's *F*-test (Kotz *et al.*, 1982 cited by Macbeth *et al.*, 2005).

3.2.4 Fecundity and oocyte development

Batch fecundity (BF) was estimated for stage 3 'ripe' pre-spawning ovaries of *A. aequidens*, a proven technique for classification of ovarian maturation (West, 1990). Gonad samples covering the full size range at each site were used. The oocyte size frequency method was used to determine BF, which involves calculations based on the most advanced modal group, believed to be the spawning batch. This has been found to produce similar results to that of using hydrated egg counts (Hunter *et al.*, 1985).

Fixed ovaries were weighed (±1 g) and 0.1 g sub-samples of tissue were removed. Tweezers were used to dislodge oocytes from connective tissue. Sample jars with oocytes were then placed in a sonic bath for 30 minutes (Unisonics FXP4) to speed up separation of oocytes from tissue (Barnes *et al.*, 2013). Collected oocytes were placed into a petri dish filled with 70% ethanol and set on top of a flatbed scanner (CanoScan 8600 F) used to produce an image. Image analysis software (Image

J Version 1.38 1) was employed to automatically count oocytes for a gravimetric estimate of BF (as described in Klibanksy and Juanes, 2008).

A pilot study was done to determine whether the vitellogenic oocyte count was affected by the location of the ovary from which sub-samples for analysis were taken (n=3). Three 0.1 g sub-samples were taken from anterior, centre and posterior sections of each ovary. The mean numbers of oocytes were compared using ANOVA to test whether counts were affected by the location of sub-sample in ovaries. The mean number of oocytes per 0.1 g sub-sample did not differ among the three sections of ovary ($F_{2,6} = 0.95$, $P=0.44$). Therefore all subsamples extracted for fecundity and oocyte distribution were taken from the centre of the gonad.

BF was calculated using the following equation:
BF=(Wg/Wss) x Nss,

where Wg is gonad weight (g), Wss sub-sample weight (g) and Nss is the number of vitellogenic oocytes counted in the sub-sample (Hunter and Macewicz, 1985).

Relative fecundity (RF) was calculated using the equation

$RF=BF\ (Wt - Wg)^{-1}$, where Wt is total weight of fish.

Linear and exponential models were fitted to BF estimates which were best explained by exponential models. An analysis of covariance (ANCOVA) was used to compare BF pooled by region with length and weight as covariates, testing for the null hypothesis of no difference in BF between the two regions. The assumption of homogeneity of variances was violated therefore mean BF values were $\log_{10}$-transformed which resulted in assumption of homogeneity to be correct ($P=0.88$). Mean RF by region was compared using an independent two-sample t-test. Assumption of homogeneity of variances was also violated therefore mean RF values were also log transformed.

Oocyte growth and development were investigated from sub-samples of a randomly chosen female gonad for all stages 2 to 5. The method described for BF estimates was used to determine diameter of oocytes and the results plotted in a frequency distribution graph for each gonad stage.

3.3 Results

3.3.1 Length distribution and sex ratios

A total of 1,378 fish were sampled, 482 from the north and 896 from the south region (Table 3.2.). A larger number of samples came from the south region due to easier access to catches at the fishermen's co-operative. The largest fish sampled was female of 86.2 cm FL from the northern site (Coffs Harbour). The largest male was 77 cm FL also from Coffs Harbour. Fish less than the MLL included in samples ranged from 9-34 cm FL for the north (n=80) and south (n=227).

The majority of fish in the fishery-dependent samples were between 35 and 55 cm FL (females 84%, males 93%) (Figure 3.2.). Average lengths of females and males were similar in each region (Table 3.2.) Length-frequency distributions of females (Figure 3.2.a, Kolmogorov-Smirnov D= 3.1, $P<0.01$) and males (Figure 3.2.b, Kolmogorov-Smirnov D= 1.9, $P<0.01$) differed significantly between the north and south regions. Pooled length-frequency distributions of males and females were significantly different during the sampling period (Figure 3.2.c, Kolmogorov-Smirnov D= 2.6, $P<0.01$). Females were more common in the north (representing 62% of sampled fish) and south (69%) regions. The sex ratio differed significantly within regions (1:2, χ^2 =105.39, df=1, $P<0.01$).

Table 3.2. Fork length (FL, in cm) of *Atractoscion aequidens* from the north and south regions.

Region/sex	Mean FL (±SE)	Max FL	Min FL	N
North				482
Female	46.7 (0.6)	86.2	31.1	275
Male	43.7 (0.5)	77	29.6	179
Immature	12.9 (0.3)	16.8	9.8	28
South				896
Female	44.7 (0.4)	84.7	20.2	599
Male	43.6 (0.5)	70.3	24.2	255
Immature	24.4 (0.6)	30.6	15.7	42
			Total	1378

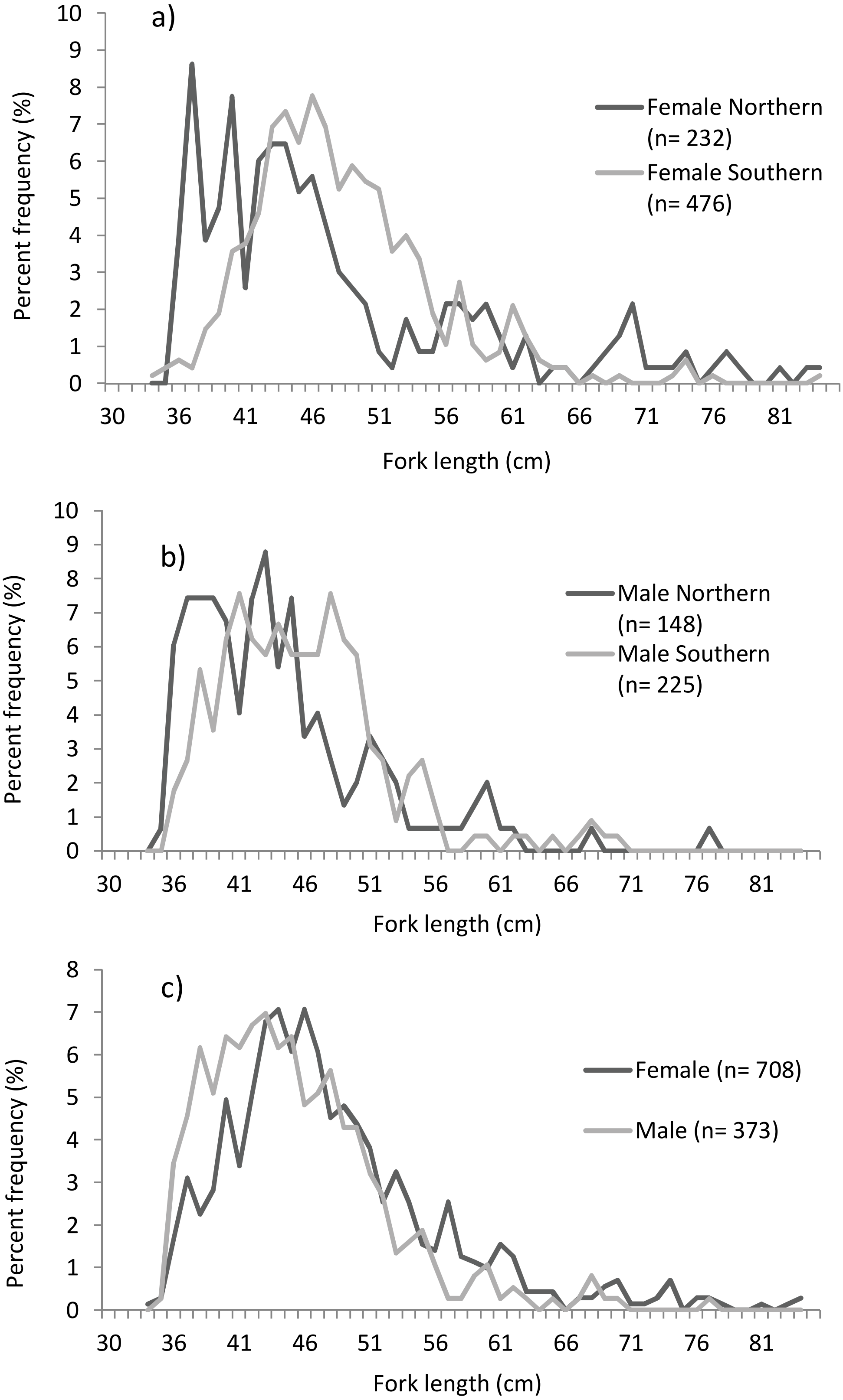


Figure 3.2. Length frequency distributions of *Atractoscion aequidens* collected from fishery-dependent samples for north and south regions: (a) females, (b) males, (c) regions pooled. The minimum legal length of *A. aequidens* in NSW is 38 cm TL (~35 cm FL).

3.3.2 Spawning period

Mean GSI pooled over the sampling period was relatively stable with a peak spawning for female *A. aequidens* in January, as shown by a peak mean GSI of ~5% (Figure 3.3.). Values then dropped to the lowest point between April and June (~2%) before increasing again to 3.5- 4% between July and December. GSI of males was lower than females, and also peaked in January (~2.5%) and was lowest (~1%) in April-June, before increasing again during July-December.

Female macroscopic staging indicates a similar pattern of reproductive activity to that of GSI (Figure 3.4.). During December - February there was a higher proportion of stage 3 and 4 female gonads, corresponding to higher mean GSI values. Conversely, during May and June there was a higher proportion of stage 2 and 5 gonads indicating resting/spent phase, and corresponding to lower GSI values. Stage 3 ‘ripe’ gonads were the most prolific gonad stage over the course of the sampling period, corresponding to elevated GSI’s for most of the year. Even though fewer stage 4 gonads were sampled over the course of the study they were evident in all months of the year.

Stage 1 immature gonads included primary growth oocytes, perinucleolar and chromatin nucleolar, with little space between oocytes (Figure3.5.a). Stage 2, developing/resting gonads, were also defined by the presence of primary growth oocytes with larger primary cortical alveolar oocytes developing. Atretic oocytes can also be present and were evident in the section (Figure 3.5.b). Stage 3 ripe gonads contained mainly vitellogenic oocytes in addition to smaller previtellogenic oocytes (Figure 3.5.c). Stage 4 running ripe gonads contained hydrated oocytes as well as vitellogenic yolk granules and previtellogenic oocytes (Figure 3.5.d.). Stage 5 spent gonads were very similar in appearance to stage 2 gonads. Cortical alveolar oocytes and primary growth oocytes were present but were less densely packed than in stage 2 gonads. Muscle bundles and atretic oocytes were also present in stage 5 ovaries (Figure 3.5.e; Brown-Peterson, 2011).

Stage 1 immature male testes contained mainly primary and secondary spermatogonia (Figure 3.6.a). Stage 2 developing/resting testes contained spermatocytes and early spermatids (Figure 3.6.b). Stage 3 testes were characterised by spermatozoa in the sperm duct and seminiferous tubules, in addition to spermatids and spermatocytes (Figure 3.6.c). Running ripe stage 4 testes were identified by an increase in spermatozoa in the seminiferous tubules and sperm duct (Figure 3.6.d). Stage 5 spent testes contained residual spermatocytes with a minimal amount of spermatids (Figure 3.6.e).

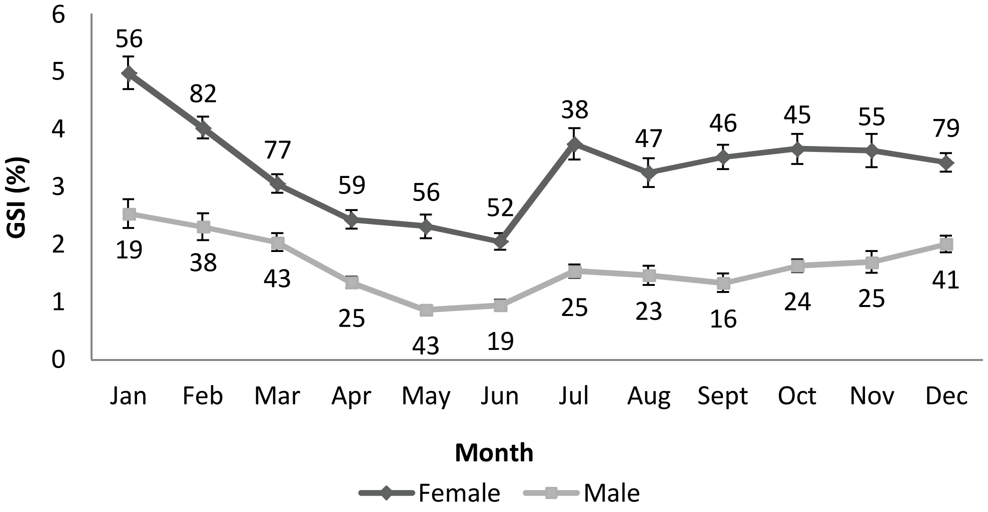


Figure 3.3. Mean GSI (± S.E) by month of male and female *Atractoscion aequidens* (samples from north and south region combined).

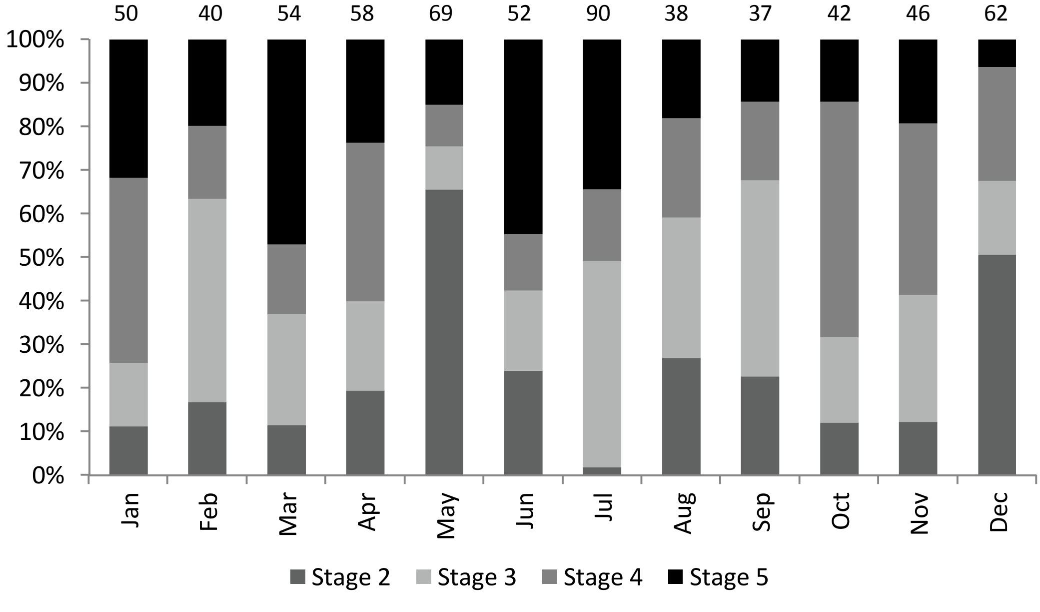


Figure 3.4. Change in the relative occurrence of Stage 2-5 gonads in samples of female *Atractoscion aequidens* from Jan 2011 to August 2012 based on macroscopic staging of gonads with samples pooled across regions and number of samples in each month shown above.

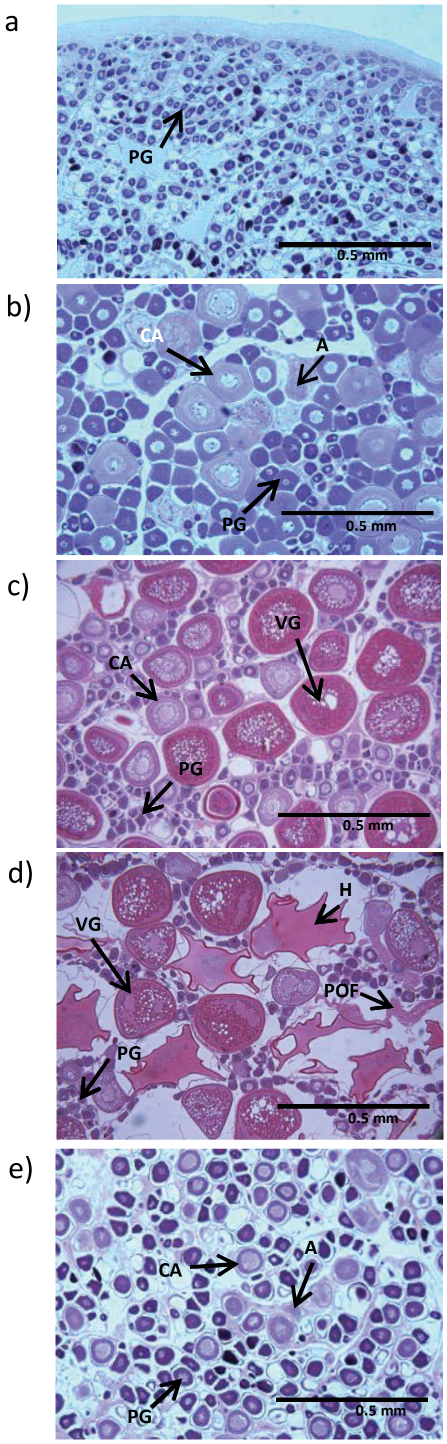


Figure 3.5. Histological sections under x10 magnification of *Atractoscion aequidens* ovarian tissue illustrating a) Stage 1 (immature); b) Stage 2 (developing/resting; c) Stage 3 (ripe); d) Stage 4 (running ripe); e) Stage 5 (spent). **A**, atretic oocyte; **CA**, cortical alveolar oocyte; **H**, hydrated oocyte; **PG,** primary growth oocyte; **POF**, postovulatory follicle; **VG,** vitellogenic oocyte.

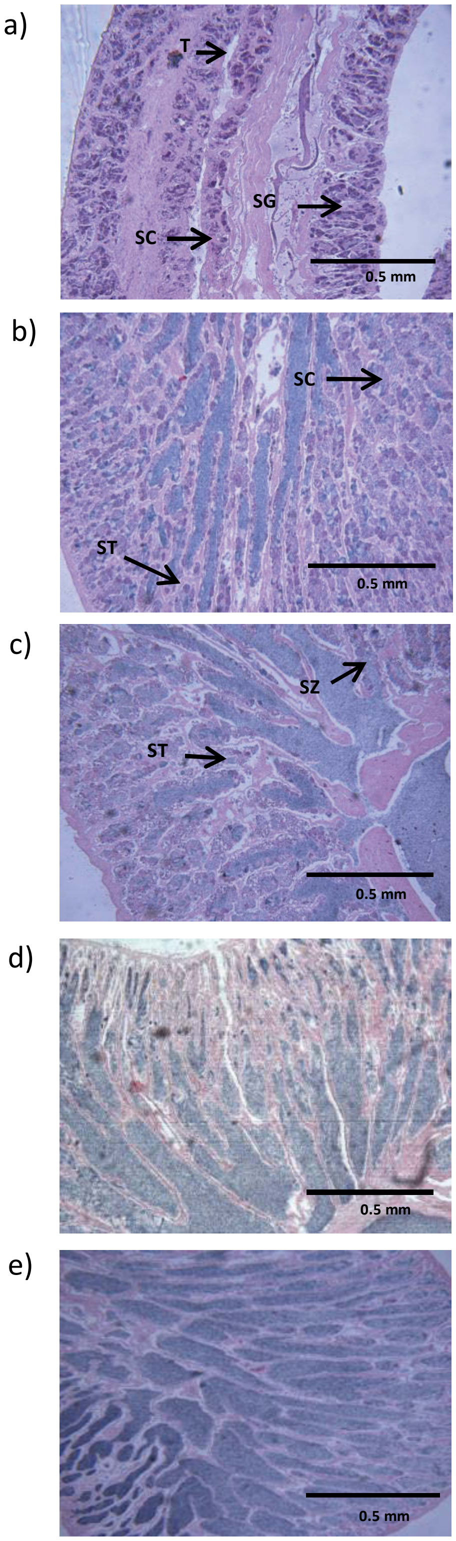


Figure 3.6. Histological sections under x10 magnification of *Atractoscion aequidens* testicular tissue illustrating a) Stage 1 (immature); b) Stage 2 (developing/resting; c) Stage 3 (ripe); d) Stage 4 (running ripe); e) Stage 5 (spent). **SC**, spermatocytes; **SG**, spermatogonia; **ST,** spermatids; **SZ**, spermatozoa; **T**, seminiferous tubule.

3.3.3 Maturity

The lengths at which 50% (L50) of females and males reached sexual maturity were 36.1 cm FL and 36.8 cm FL respectively (Figure 3.7.). All females were mature at 45 cm FL and all males at 49 cm FL. The L50 of males and females were not significantly different when compared using Wald's test (*P*>0.05).

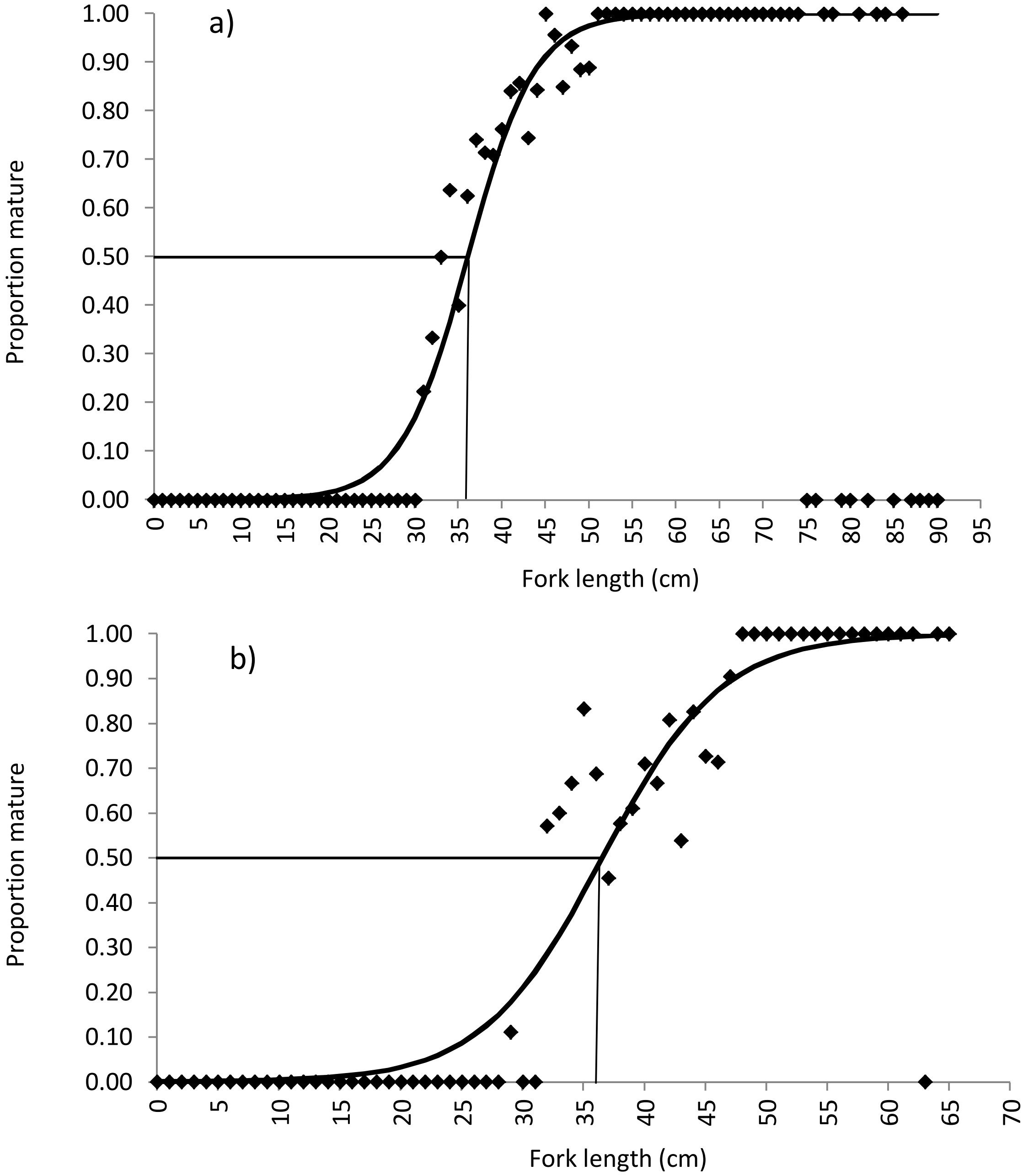


Figure 3.7. Length at maturity with fitted logistic curves for *Atractoscion aequidens* in NSW for a) females and b) males .

3.3.4 Fecundity

BF based on the most advanced mode of stage 3 vitellogenic oocytes ranged from 26,207 ± 3,331 (mean ± S.E.) for a 33.2 cm FL fish to 484,324 ± 20,933 (mean ± S.E.) for a 58.3 cm FL fish, both from the south region. In the north region BF ranged from 33,043 for a 43.2 cm FL to 413,902 for a 71.5 cm FL fish. On average, BF was higher in the south (219,712 ± 29,137, n=20) compared to the north region (150,391 ±24,986, n=17).

The relationship between BF and length was best described by the exponential relationship BF=9,443*(exp$^{0.048\ (FL)}$) (r^2=0.69) in the north and BF=1,582*(exp$^{0.0929\ (FL)}$) (r^2=0.72) in the south (Figure 3.8.). The relationship between BF and body weight (BW) was best described by the exponential relationship BF=51,041*(exp$^{0.0005\ (BW)}$) (r^2=0.72) in the north and BF=26,976*(exp$^{0.0014\ (BW)}$) (r^2=0.74) in the south.

Due to the exponential relationship between fish size and BF, data were log transformed to complete ANCOVA with body weight and fish length as covariates. One-way ANOVA's were performed to ensure body weight and fish length were independent of BF in the north and south. ANCOVA found BF was significantly different between the north and south (Table 3.3.; F=10.44, *P*<0.05).

Relative fecundity (RF) in the north ranged from 44–159 oocytes per gram of body mass and 62 – 292 oocytes per gram body mass in the south. Mean RF in the north (96 ± 8; n=17) was significantly lower than mean RF in the south (168 ± 15; n=19) (t=4.004, *P*<0.05).

Table 3.3. Summary of results of analysis of covariance testing for the effects of region on batch fecundity of *Atractoscion aequidens* with length and body weight as covariates.

Source	Type III SS	df	MS	F	P
Corrected Model	2.36^a	3	0.79	21.72	<0.001
Intercept	1.58	1	1.58	43.48	<0.001
Length	0.24	1	0.23	6.53	0.02
Bodyweight	0.02	1	0.02	0.58	0.45
Region	0.38	1	0.38	10.44	0.003
Error	1.16	32	0.04		
Total	968.07	36			
Corrected Total	3.52	35			

a. R Squared =0.67 (Adjusted R Squared =0.64)

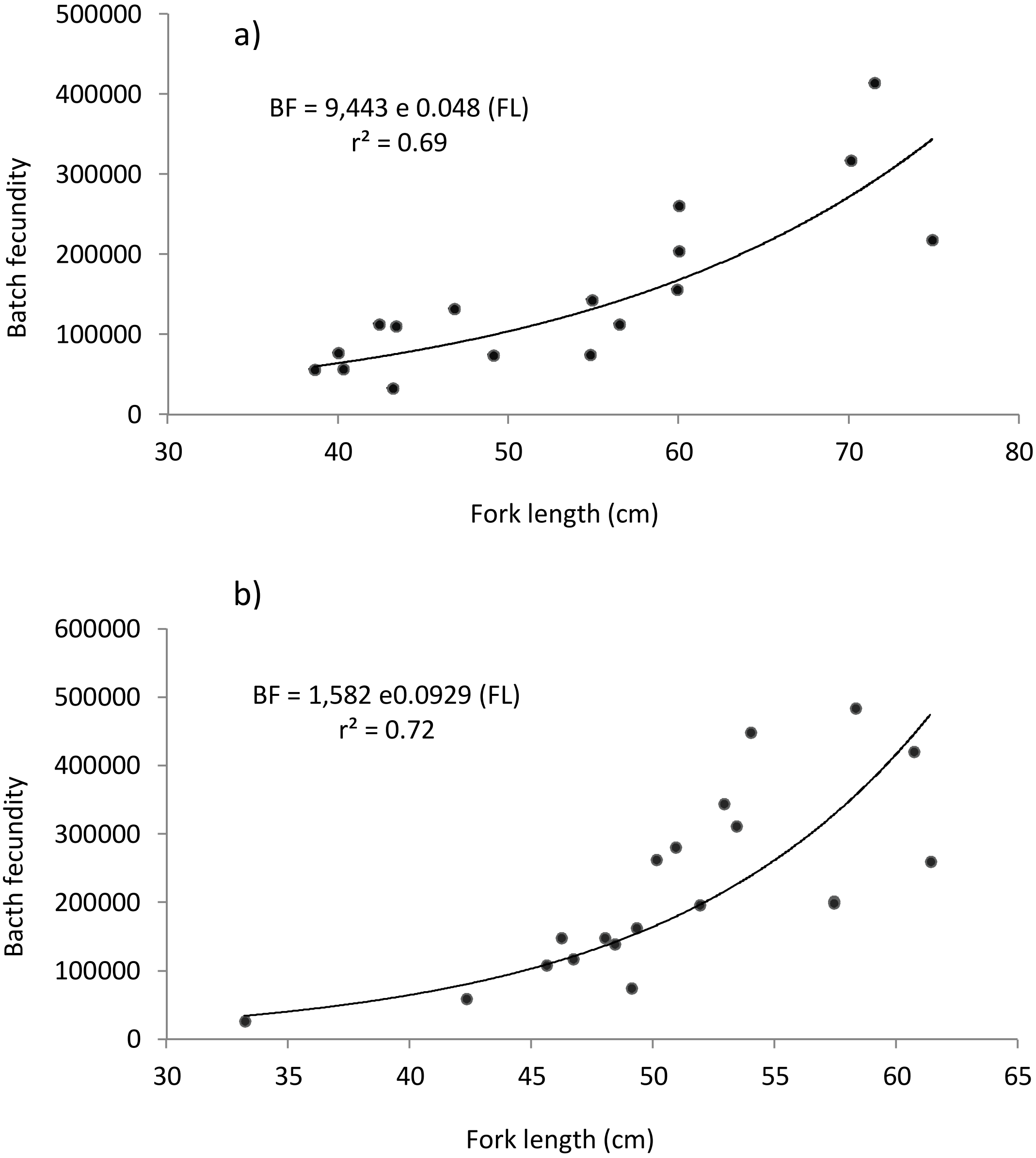


Figure 3.8. Exponential relationship between fork length (cm) and batch fecundity for female *Atractoscion aequidens* a) north region (n=17) and b) south region (n=19).

3.3.5 Oocyte development

Stage 2 female gonads were dominated by a single mode of oocytes of diameter 0.1-0.3 mm (Figure 3.9.a). Stage 3 gonad consisted of 2 modes of oocytes: 0.1–0.35 mm and 0.5-0.7 mm (Figure 3.9.b). Stage 4 gonad consisted of oocytes 0.1-0.5 mm and two distinct modes ranging in size of 0.55-0.65 mm and a second mode of hydrated oocytes between 0.8-0.97 mm in diameter (Figure 3.9.c). Stage 5 gonads displayed oocytes mainly in the diameter range of 0.1-0.25 mm. Another mode of oocytes was evident between 0.5-0.6 mm (Figure 3.9.d).

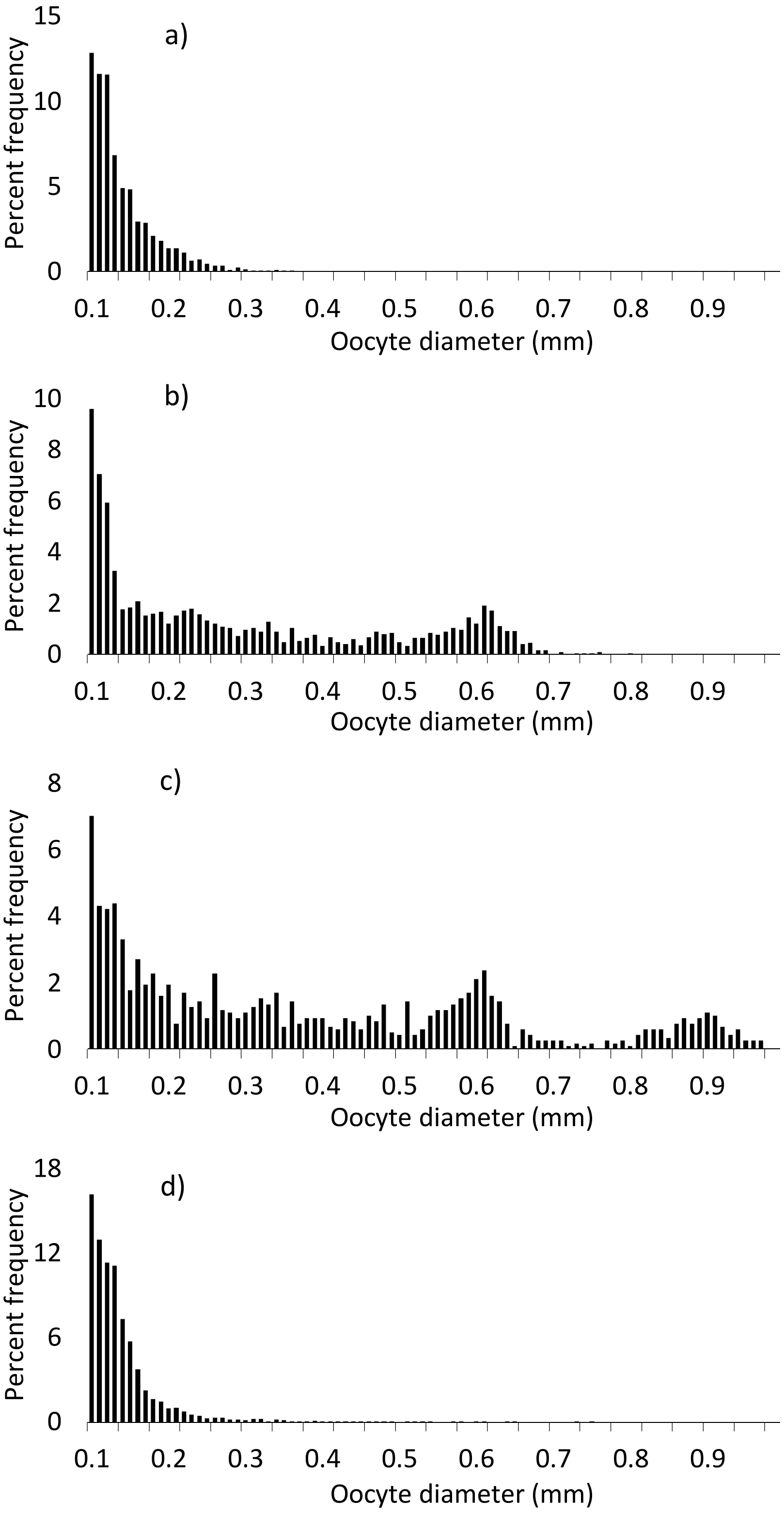


Figure 3.9. Oocyte size frequency for a) stage 2 ‘developing/resting’, b) stage 3 ‘ripe’, c) stage 4 ‘running ripe’ and d) stage 5 ‘spent’ *Atractoscion aequidens* female gonads stored in ethanol solution. Note differences in scale on y axis.

3.4 Discussion

3.4.1 Length distribution and sex ratios

The largest fish sampled during the study was 86 cm FL (91 cm TL) and 6.4 kg from Coffs Harbour and estimated to be approximately 10 yr from otolith ageing (see Chapter 4). This was very similar to the maximum size and age reported for the species in QLD (Sumpton *et al.*, 2013) but much smaller than South Africa where the species grows to 130 cm TL and 25 kg (Griffith, 2000a). It is also smaller than the previously reported maximum size and weight for *A. aequidens* in NSW of 100 cm FL and 10 kg (Hutchins and Swainston, 2006). The reason for a smaller maximum size than has been previously reported may be due to sampling effect of the fishery-dependant collection. Larger fish may not be accessible to all areas of commercial fishing. In addition, it has been documented that within populations there are trade-offs between somatic growth and reproduction (Folkvord *et al.*, 2016). The species may be investing more energy into reproductive output rather than growth. In South Africa, the species is much larger and undertakes a spawning migration indicating that resources are allocated to growth until sexual maturity is reached at 5 yr and 90 cm TL (Griffiths and Hect, 1995). The larger size of *A. aequidens* in South Africa is consistent with findings that species that undertake large migratory spawning patterns are typically larger (Roff, 1988; Clardy, 2004).

Male *A. aequidens* were on average smaller than females but the length frequency distributions of the two sexes did not differ. In contrast, females are typically much larger than the males in *A. aequidens* in South Africa (Griffiths and Hecht, 1995a) and in many other species of sciaenids, (e.g. mulloway, white seabass, dusky cob, see Appendix A). It is well known that female body size is positively correlated to fecundity highlighting the importance of larger, older fish in a population (Hutchings, 2000; Berkeley *et al.*, 2004; Green, 2008).

Atractoscion aequidens in the south of NSW were larger than fish from the north. This may be related to differing depths commercial fish were caught reflecting a sampling effect of the study. Alternatively, the waters off Forster are highly productive due to the upwelling of the EAC where the main current detaches from coast (Godfrey *et al*. 1980; Ridgway and Dunn, 2003) which may result in faster growth and resources into fish size, which then in turn results in higher fecundity. In QLD, Sumpton *et al*. (2013) found that *A. aequidens* were larger in deeper, offshore waters, indicating depth related size stratification. Differences may also be attributable to a higher proportion of smaller fish in the north region than in the south at the time of sampling. To investigate the significant difference between the two sampling regions, commercial catch records could be used to determine depths and any correlation with fish size. In addition, length monitoring over multiple years may also highlight if it was in fact a sampling effect or the differences are due to environmental factors.

Significantly more females were sampled during the study than males. While this was not found to be the case in QLD, Sumpton *et al*., (2013) found evidence that the species schooled by sex. *Atractoscion aequidens* in NSW may also be schooling by sex, or it may be an artefact of a complex social structure, which has been found in other sciaenids (Lowerre-Barbieri *et al*., 2009; Tellechea *et al*., 2011).

Differences in sex ratios similar to that found for *A. aequidens* in NSW were also found in sciaenids *Umbrina robinsoni* (Hutchings and Griffiths, 2010) and *U. canariensis* (Hutchings, 2006) in South Africa. Their explanation for the skewed sex ratios was that females reside in the highly productive surf zone to replenish energy requirements in between spawning events and males (having less energy requirements) were located farther offshore on spawning grounds (Hutchings, 2006; Hutchings and Griffiths, 2010). Additionally, *A. aequidens* has been documented to be highly voracious (Griffiths and Hecht, 1995a; Stewart *et al*., 2015) and with year-round spawning activity, females may be baited by commercial handlines more easily due to the higher energy requirements of oocyte development. The teleost *Mahi mahi* (dolphinfish), which also spawn all year-round, are also voracious feeders (Alejo-Plata *et al*., 2011). Further research of the skewed sex ratio is needed for fish under the MLL and over different spatial and temporal scales with higher sample sizes to determine if the sex ratio found in this study is a reflection of the population.

3.4.2 Spawning season

Atractoscion aequidens exhibited asynchronous oocyte development and year-round spawning behaviour. Asynchronous oocyte development is common within the family Sciaenidae, commercially exploited and epipelagic fish (Murua *et al.*, 2003; Sadovy, 2003; Lowerre-Barbieri *et al*., 2011). This form of oocyte development is common in species with a protracted spawning season and is important for a constant supply of vitellogenic oocytes, potentially allowing for greater resilience to fishing pressure (Frank & Brickman 2001; Lowerre-Barbieri *et al*., 2013). All stages of oocyte development were sampled during the study indicating that *A. aequidens* most likely completes its life cycle in the marine environment, unlike some euryhaline sciaenid species (*A. japonicus,* Silberschneider and Gray, 2005; *A. regius,* Gonzalez-Quiros *et al*., 2003; *Cynsocion nebulosus,* Bortone, 2003).

A review of literature on spawning seasons within the family Sciaenidae found *A. aequidens* reproductive parameters to be unique. As mentioned by Lowerre-Barbieri *et al*. (2011), fish typically display seasonality in peak spawning and reproductive cycles on an annual basis (Rideout *et al*., 2005). *Atractoscion aequidens* however displayed constant supply of vitellogenic oocytes, indicating that fish were capable of spawning through-out the year (Brown-Peterson *et al*., 2011). Increased reproductive activity, demonstrated by increased GSI and presence of stage 3 and 4 gonads in macroscopic staging of females, occurred during September-February. A secondary increase was evident during the winter period May-July, indicating that for most of the year *A. aequidens* are reproductively active, which was also found in QLD (Sumpton *et al*., 2013). This was validated by the histology of stage 4 gonads, which had both postovulatory follicles (POFs) and oocytes undergoing oocyte maturation. This suggests frequent spawning as oocytes in a batch undergo maturation quickly and may be expelled in the same spawning event (Brown-Peterson 2002; Jackson *et al*., 2006 in Brown-Peterson 2011). While only small numbers of stage 4 females gonads were observed, similar to results of *A. aequidens* in QLD (Sumpton *et al*., 2013), the hydration of oocytes can take place over a short time frame (~24 hr; E.g. *Cynoscion nebulosus*, Brown-Peterson, 2002) and therefore may be uncommon to encounter.

Additionally, late migration of the nucleus stage (typical of stage 4) is not macroscopically detectable and as such may have been assigned stage 3 (West, 1990).

A spawning season extending over much of the year is typical for warmer-water species (Pavlov *et al*., 2009 in Lowerre-Barbieri *et al*., 2011), however not frequently observed for commercially exploited species in the temperate waters of NSW. In contrast, the findings by Griffiths and Hecht (1995a) of *A. aequidens* in South Africa displayed a 3 mo spring-summer spawning season with associated migratory patterns, which has not been suggested for the NSW stock. A similar pattern of reproductive activity was found for the congeneric species, *A. nobilis,* whereby they exhibit a peak in spawning activity over a 3 mo period during spring-summer in North America, which is typically found for many sciaenids (Appendix A; Vojkovich and Reed, 1983; Donohoe, 1997; Lowerre-Barbieri *et al*., 2009, Waggy *et al*., 2006; Clardy *et al*., 2011). Other sciaenids of similar life history characteristics and spawning season (7-10 mo) to *A. aequidens*, grew to a much smaller maximum size and displayed much smaller length at maturity. For example, the white croaker (*Genyonemus lineatus*), which has a 7-10 mo spawning season, attains a maximum length of 41 cm TL (Waggy *et al*., 2006; Clardy *et al*., 2014).

Atractoscion aequidens contain sonic muscles indicating they are capable of grunting noises and may have complex courtship rituals like that of *A. nobilis* (Aalbers, 2008) and *Micropogonias furnieri* (Tellechea *et al.,* 2011). Drumming noise in *M. furnieri* was found to peak in January coinciding with peaks in GSI. This has been noted for many other sciaenids such as spotted seatrout, black drum, red drum and silver perch (Lowerre-Barbieri *et al*., 2009; Tellechea *et al*., 2011). Further research employing the use of passive acoustic sampling techniques such as hydrophones may be beneficial to determining spawning strategy in *A. aequidens* and determining if complex courtship relationships exist between males and females. It would also assist in determining whether specific spawning grounds are used by *A. aequidens,* which would be important for management of the species.

Further research on spawning season using spatially and temporally stratified histology samples to determine percentage of running ripe and resting gonads would assist in more detailed information for this species, such as rates of atresia, spawning fraction and any signs of skipped spawning. Determining the spawning fraction would require considerably more resources, using the elapsed time per spawning event in a laboratory controlled experiment with live fish, as post ovulatory follicles degenerate too quickly (in warm-water species, 24-48 h after spawning) meaning they may not be a viable indication of previous spawning (Hunter and Maceweiz, 1985; Priede and Watson, 1993). Skipped spawning has been found in numerous species (for review see Rideout *et al.*, 2005) and is often unaccounted in fisheries population modelling (Rideout *et al.*, 2010) and poorly understood in many species (Jørgensen *et al.*, 2006). While skipped spawning may occur for *A. aequidens,* accounting for it may be too difficult to ascertain due to the year-round spawning pattern the species displays. Determination of skipped spawning is possible only in species with a defined spawning period as POF's deteriorate over time and may not be visible in spent fish (Rideout *et al*. 2005). Calculation of rates of atresia would be a better indication of possible reductions in batch spawning values. Rates of atresia have found to be correlated to productivity and temperature (Rideout *et al.*, 2006) so it would be of interest to study gonad condition during different times of the year for *A. aequidens* in more detail.

3.4.3 Maturity

Compared to other sciaenids, *A. aequidens* mature at a smaller size in NSW (Appendix A). Early maturation has been associated with faster growth rates in other teleost species (Morgan and Colbourne 1999; Haugen, 2000). However, many sciaenids have developed a strategy to mature in the first year of life, which may be attributable to heavy fishing pressure as sciaenids in many parts of the world are targeted heavily by recreational and commercial fisheries (Waggy *et al.*, 2006; Helfman *et al.*, 2009; FAO, 2011). Male and female *A. aequidens* in NSW mature at a similar size of approximately 36 cm FL. In QLD, Sumpton *et al.* (2013) found the species matures at ~34 cm FL. However, QLD researchers did indicate difficulty in obtaining fish under the MLL and were cautious about their results for length at maturity. Both of these findings differ markedly to the results for the same species in South Africa where maturity occurs at a much larger size of 90 cm FL. Due to the cosmopolitan distribution of species in the family, life history differences are common for other sciaenid species which have intra-specific variations in reproductive traits such as size of maturity and duration and timing of the spawning season (*A. japonicus;* Griffiths and Hecht, 1995b; Griffiths, 1997; Farmer *et al*., 2005; Silberschneider and Gray, 2005, 2009; Ferguson and Ward, 2011).

Within the sciaenid family, females typically attain sexual maturity at larger sizes than males, due to females investing more resources into reproductive output (Griffiths and Hecht, 1995a, 1995b; Lowerre-Barbieri *et al*., 1996; Bortone 2003; Silberschneider and Gray, 2005; Farmer *et al.,* 2005; Hutchings *et al*., 2006; Gonzalez-Quiros *et al*., 2011). A comparative reproductive biology study on seven species of sciaenids in Argentina (Militelli *et al*., 2013) also found females mature at larger sizes than males. An extensive literature search of species similar to *A. aequidens*, found only one species where males and females attained sexual maturity at a similar size (Appendix A; *A. japonicus* South Australia*;* Ferguson and Ward, 2011).

Male length at maturity can be difficult to ascertain. Macroscopic maturity scales for male meagre (*Argyrosomus regius)* do not adequately represent the various stages of male maturity (Prista *et al*., 2014). When comparing macroscopic and histological classification on testicular reproductive development, a high proportion of small fish were classified as ripe however in histological analysis were found to be immature. Prista *et al*. (2014) found that milt extrusion used in macroscopic classification of maturity was not a reliable indicator of maturity in *A. regius*, incorrectly assigning 50% of ripe fish as immature and 83% of spent/resting fish as immature (n=27). This is a challenge that is frequently found in macroscopic maturity classification of testes, distinguishing between fish that are spent/resting and those that are immature (Prista *et al*., 2014). Further, their study validated the occurrence of males that had low GSI and may or may not extrude milt but were mature based on histology with the presence of spermatozoa and therefore capable of reproducing (Brown-Peterson *et al*., 2011). This illustrates that milt extrusion should not be used alone in maturity ogives and histological validation is imperative in assigning male maturity classes in sciaenids. While this raises concerns for the maturity classification of male *A. aequidens,* the species displays a markedly different reproductive strategy to *A. regius*. Male *A. aequidens* demonstrated a protracted spawning season based on GSI, which was relatively high compared to other sciaenids. GSI in *A. regius* dipped to a low of 0.51% in resting/spent fish and a high of 3.45% in spawning capable fish. Mean GSI of *A. aequidens* dipped to a low ~ 1% for only two months and a peak of 2.5%, while for the majority of the year the GSI was stable at 1.5-2%. Similar to the results found for females, male *A. aequidens* are likely to be serial spawners, shedding milt over much of the year. However, caution must be applied to the results of length at maturity for males, as there was no validation of maturity stage based on histological analysis of testes.

3.4.4 Fecundity

There was a positive relationship between length/weight and BF and was best described by an exponential relationship. This highlights the importance of larger fish to the spawning potential of the *A. aequidens* population with larger fish producing an increase in oocytes per batch spawned relative to smaller fish. However, the maximum reported size of 100 cm FL (Hutchins and Swainston, 2006) has not been seen for quite some time, suggesting that *A. aequidens* may be experiencing a high rate of exploitation. Studies have also shown the larvae produced from smaller, younger fish do not grow as fast or withstand starvation as well as larvae spawned from older, larger fish (Hutchings, 2000; Berkeley *et al*., 2004; Green, 2008).

BF estimates of *A. aequidens* are similar to those found for other sciaenids, notably species in the genus *Cynoscion*. BF for *A. aequidens* ranged from 26,207 to 484, 324, which might be multiplied by many spawnings in a year, indicating relatively high fecundity. Previous research has demonstrated that individuals with a protracted spawning season often have a significant variation in fecundity estimates (Lowerre-Barbieri *et al*., 2009). BF was higher in the south compared to the north region. Results were significantly different even when accounting for any effect of fish size between the north and south regions. Relative fecundity ranged from 44 – 292 and was significantly higher in the south region. This suggests that the area around Forster may be contributing a significant proportion of recruitment to the overall NSW stock assuming all other factors such are population size, length distributions and ages are equal.

While fecundity is obviously important to the replenishment of a stock, the relative importance of other factors has also been raised. Berkeley *et al*. (2004) and Hutchings & Reynolds (2004) argue that the ultimate driving force for a population's success may in fact be a smaller number of individuals driven by a complex number of temporal, spatial and demographic factors.

3.4.5 Conclusion

Knowledge of species life history characteristics, in particular reproductive strategies, is vital for long-term sustainability of exploited species. This was the first study to determine the reproductive parameters of *A. aequidens* in NSW. The species exhibits resilient reproductive strategies such as asynchronous oocyte development, year-round spawning and smaller length/age at maturity than many other sciaenids that are exploited.

Based on a review of a large number of studies on sciaenid life history characteristics, *A. aequidens* displayed unique reproductive strategies (Appendix A; Waggy *et al*., 2006; Clardy *et al*., 2011), including year-round spawning activity. Other sciaenids that have a prolonged spawning season (>6 months) tend to have a much smaller maximum size (<45 cm TL) than *A. aequidens*. The length at which 50% of the population was mature was close to the current MLL (38 cm TL), which at first may appear to provide an appropriate level of protection of the spawning population from the effects of fishing. However in the absence of any historical data on the length at maturity in a lightly fished population of *A. aequidens*, a fishery induced reduction in the length at maturity cannot be dismissed. Reduction in length at maturity has been reported for other exploited sciaenids.

Chapter 4: Age, growth and mortality rates of *Atractoscion aequidens* in New South Wales, Australia.

Abstract

Growth rates, age distributions and mortality rates are essential biological parameters underpinning management of a stock. Despite a long history of exploitation, this is the first study to estimate length-at-age of *Atractoscion aequidens* (family Sciaenidae) in New South Wales (NSW). The aim of this study was to estimate length-at-age using sagittal otoliths and validate annual opaque zone formation. *Atractoscion aequidens* is fast growing reaching approximately 40 - 45 cm FL in the first year of life and can reach up to 14 yr. Growth rates between sexes were significantly different with modelled asymptotic lengths indicating females grow to larger lengths (L_∞=84.6 cm FL) than males (L_∞=69.0 cm FL). The largest female sampled during the study was 86 cm FL (10 yr) and for males was 77 cm FL (14 yr). While growth between sampling regions was found to be significantly different, mean length-at-age indicated similar growth rates until about 6 yr. Marginal increment analysis validated the formation of annual opaque zone formation with zones generally laid down during September-January. In conjunction with length-at-age data, length frequency distributions (n=6,000) were used to develop an age-length-key to estimate the commercial age distribution in NSW. The commercial fishery is predominantly based on young fish < 3 years with few over 5 yr (5%). Fishing mortality estimates (F=0.42) were roughly equal to natural mortality estimates (M=0.44). Mortality estimates indicate a constant rate of mortality between age classes, with no sign of significant variation in year class strength during the study period. Determining the age distributions and growth and mortality rates of an exploited species is an important component of the development of any quantitative stock assessment.

4.1 Introduction

Age and growth parameters such as growth and mortality rates are the most important life history and population characteristics needed to understand the productivity and resilience of exploited fish populations (Lowerre-Barbieri *et al*., 1996; Campana, 2001; Campana and Thorrold, 2001). Determining these parameters is paramount to ensure fishing mortality rates do not exceed the ability of a species to naturally replenish. Further, heavy exploitation of a stock can lead to decreased resilience to environmental changes therefore it is imperative to determine life history characteristics to ensure sustainability (Hsieh *et al.,* 2006).

Species within the family Sciaenidae support many significant commercial and recreational fisheries worldwide (Paxton and Eschmeyer, 1994). The large sizes attained by many species within the family make them highly prized and targeted within recreational and commercial fisheries (Sadovy and Cheung, 2003). Reaching sexual maturity at large sizes also results in a predisposed risk to overfishing and significant declines during the last few decades have been reported for several species e.g. *Sciaenops ocellatus*, (Ross *et al.*, 1995); *Argyrosomus japonicus* (Silberschneider and Gray, 2005); *Totoaba macdonaldi* (Potts *et al*., 2010); *Argyrosomus inodorus* (Griffiths, 1997) and *Atractoscion nobilis* (Hervas *et al.,* 2010).

In New South Wales (NSW) there are two species of sciaenid: teraglin, *A. aequidens* (Cuvier, 1830) and mulloway, *A. japonicus* (Temminck & Schlegel, 1843). While the life history of *A. japonicus* in NSW is understood (Silberschneider and Gray, 2005), no study has been done on the life history of *A. aequidens* in NSW, despite the species' long-history of exploitation. Landings of *A. aequidens* by the NSW commercial fishery peaked in the mid-1950s reaching over 200 t however recent landings have been around 20-30 t (Stewart *et al.,* 2015) with the recreational catch being similar (~37 t; West *et al.,* 2015).

Atractoscion aequidens is found off the east coast of Australia from Double Island Point (25.93°S, 153.18°E) in south-east Queensland (QLD), where catches are important in the charter-boat fishery, to Montague Island (36.15°S, 150.13°E) on the south coast of NSW (Figure 4.1.) (Steffe and Neira, 1998; Hutchins and Swainston, 2006). In NSW they inhabit the continental shelf over broken gravel or reef at depths of 20-80 m and have been reported to reach a maximum length of 100 cm total length (TL) and weight of 9 kg (Hutchins and Swainston, 2006). The same species is found off the coast of South Africa, but grows to a much larger length and size, 130 cm TL and 25 kg respectively (Griffiths, 2000a). For both *A. aequidens* and *A. nobilis*, the only other congeneric species, there is limited information on growth. *Atractoscion nobilis* too has a long history of exploitation in both commercial and recreational fisheries in the Pacific Ocean sharing many similar traits to that of *A. aequidens* in South Africa, such as large size and age at maturity, spawning migrations and large maximum length and size (Romo-Curiel *et al.,* 2015; Griffiths and Hecht, 1995a; Donohoe, 1997). The species has been recorded at a maximum length of 160 cm TL and weight of 40 kg (Donohoe, 1997).

The use of hard parts in fish, in particular the sagittal otolith, is widely regarded as the most accurate method for the determination of growth parameters and age structures in exploited fish populations, including many sciaenids (Lowerre-Barbieri *et al.*, 1994; Griffiths and Hecht, 1995b; Campana, 2001; Silberschneider *et al.*, 2009). In such a specious family (over 280 species; Froese and Pauly, 2011), there is a wide range of maximum age and age structures in exploited sciaenids. Large, trophy sized sciaenids are long-lived with females growing larger, such as *A. japonicus* in both NSW (35 yr; Fisheries NSW unpublished) and South Africa (42 yr; Griffiths and Hecht, 1995b) and *A. nobilis* in southern California (27 yr; CDFG, 2002). Fisheries also exist based on smaller and younger sciaenids, *Cynoscion regalis* (8 yr; Lowerre-Barbieri, 1995) and *Larimichthys polyactis,* (~40 cm; FAO, 2011). Geographical differences in age structures and maximum size have been found on large scales between the sciaenids of South Africa and Australia (*A. japonicus*; Silberschneider and Gray, 2005; Griffiths and Hect, 1995b) and on smaller scales within species populations (*C. regalis*; Lowerre-Barbieri, 1995). Differences in growth rates over spatial scales have also been found for other temperate species found in NSW such as *Trachurus novaezelandiae* (yellowtail scad; Stewart and Ferrell, 2001), *Girella elevate (*Rock blackfish; Stocks *et al.,* 2014) and *Arripis trutta* (eastern Australian salmon, Hughes 2012).

The aim of the current study is to quantify the age and growth parameters of *A. aequidens* in particular: (i) validate use of sagittal otoliths to quantify age by analysing annuli in the otoliths of *A. aequidens*, (ii) the growth rates and longevity of males and females, (iii) geographical variation in age and growth, and (iv) the age composition and mortality rates for commercially exploited *A. aequidens* in NSW with the employment of an age-length key. The results will be compared with growth parameters for the same species from South Africa and QLD and provide essential information for management to ensure sustainable harvest of the exploited stock in NSW.

4.2 Methods

4.2.1 Sampling sites and data collection

Fishery-dependent biological samples caught commercially on handline were collected monthly from three fishermen's co-operatives between January 2011 and June 2012, corresponding to major ports of commercial landings for *A. aequidens* in NSW (Figure 4.1.) The three sampling sites were Evans Head (29.12° S, 153.43° E), Coffs Harbour (30.30° S, 153.12° E) and Forster (32.18° S, 152.51° E). Sites were divided into north (Evans Head and Coffs Harbour) and south regions (Forster). The two regions correspond to two distinct areas of the western boundary current, the East Australian Current (EAC). The north region is dominated by warmer and nutrient poor water from the Coral Sea and the south region is characterized by the highly variable separation zone of the EAC, where the main current detaches from the coast (Godfrey *et al*., 1980; Ridgway and Dunn, 2003; Suthers *et al*., 2011). Growth rates in teleosts have been correlated with oceanic temperature and food availability (Hazell, 1993 in Threser *et al*., 2007). The north and south regions have differences in nutrient availability and sea surface temperature that may result in a difference in growth rates, maximum size and age composition of *A. aequidens* in NSW. Pooled growth rates and age structures of *A. aequidens* in the two regions were compared to determine if they were affected by the different environmental conditions of the north and south regions.

Fishery-dependent sampling involved the collection of ten fish selected at random each month from commercial landings at each sampling site. For each fish, fork length (±0.1 cm), body weight (±1 g), sex, gonad weight (±0.1 g), and gonad maturity stage were recorded and both sagittal otoliths were removed. Otoliths were cleaned and dried on paper and stored in paper envelopes with a unique identifying code recorded for each fish. Sagittal otoliths were weighed (± 0.00001g) using an electronic balance (Sartorius CP225D). Gonad maturity was determined from the macroscopic appearance of gonads (see Table 3.1). To increase the size range of fish sampled, fish smaller than the minimum legal length (MLL, 38 cm total length TL) were collected from the north region at Iluka (just south of Evans Head; Figure 4.1.) using handlines and from the south region at Forster from commercial fishermen using trawl nets. Sporadic samples from the recreational fishery for *A. aequidens* were obtained from fishermen in Sydney and at fishing competitions in Evans Head (length, otoliths and sex only, n=151). A pilot monitoring study on *A. aequidens* completed from commercial samples collected predominantly at Forster (covering 2006-2009, n=330) was also included in analyses. The total number of samples collected in the north was 559, and in the south 931.

Additional length frequency data from fish in commercial landings were also collected during the sampling period as part of a state government fishery-dependent sampling program run by Fisheries NSW. Whole catches were measured and lengths recorded to the nearest whole cm (rounded down). Sex-based estimates were not possible for these data.

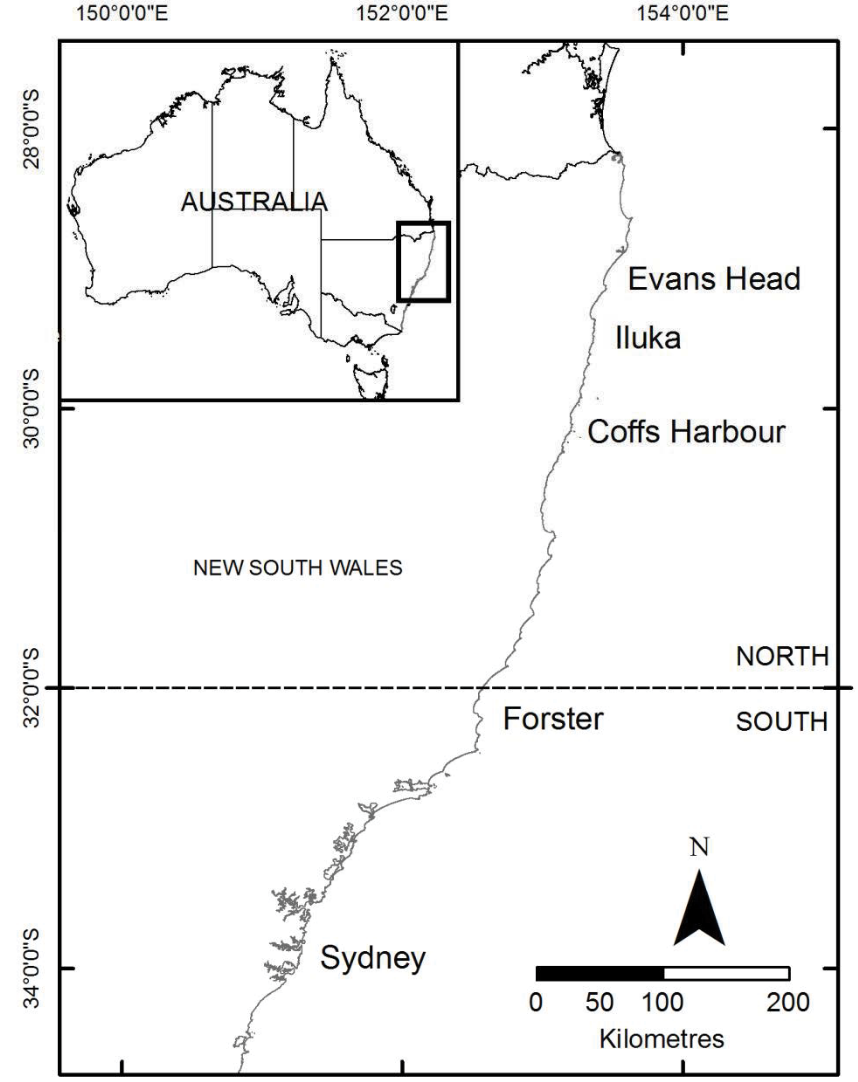


Figure 4.1. Map of NSW coast showing the locations of sites where *Atractoscion aequidens* was sampled. Dashed line indicates the separation of north and south sampling region (see text for explanation).

4.2.2 Otolith processing

Sagittal otoliths were embedded in resin blocks and multiple 0.6 mm sections were transversely cut through the core using a diamond saw (Gemmasta, Shelleys Lapidary, South Australia). Sections were mounted on glass slides and polished using a Struers LaboPol-4 polishing machine (Struers Australia, Milton, Queensland, Australia) with 500 grit silicon carbide paper. Polished samples were then cover-slipped with resin and observed under a compound microscope using reflected light with x 2 objective lens (Olympus BX41, Tokyo, Japan). Age estimation was determined by counting annuli, observed as opaque zones, along the sulcus acusticus starting from the primordium to the outer edge of the ventral lobe (Figure 4.2.). Images of sections were taken with a camera mounted to the microscope (Q-Imaging, MicroPublisher 5.0 RTV, Canada). Image J software (http://rsb.info.nih.gov/ij/) was used to count opaque zones and calculate increment widths.

4.2.3 Age estimation and marginal increment analysis

Due to the protracted spawning period *A. aequidens* exhibits in NSW (9 mo, see Chapter 3) a universal birth date could not be assigned. For many species of teleosts (and sciaenids), a spawning season typically lasts 3-6 mo (Appendix A; Lowerre-Barbieri *et al.*, 2009, Clardy *et al,*. 2011) and species are assigned a birthdate, often the midpoint of the identified spawning season (Stewart and Hughes, 2007). This allows counts of annuli to be converted to age classes and if desired fractional yearly ages can be determined from the birthdate and date of sampling. For *A. aequidens* the number of annuli counted will be referred to as the age in years (*sensu* Campana, 2001). As Campana (2001) confirms, the actual age of a fish is rarely confirmed in absolute terms, in fact it is the frequency of the formation of the opaque zones that should be validated. So here the periodicity of opaque zone formation is validated rather than the absolute age of *A. aequidens*.

Marginal increment analysis (MIA) was used to determine and validate the periodicity and timing of opaque zone formation in *A. aequidens* in NSW. Marginal increments (MI) were calculated as the distance from the otolith edge to the outer edge of the last formed opaque zone as a proportion of the last completed increment.

MIA was undertaken by pooling age classes 1-2 (n=867) and 3-14 (n=367) and comparing mean monthly MI (± S.E) during a 12-month period to observe any seasonal differences in opaque ring formation between the two groups. Comparing the two sets of age ranges is important as there can be variability in the timing of opaque zone formation based on age class (Campana, 2001). MI values close to one indicate that an increment has almost fully formed, and MI values close to zero indicate that an increment has recently been completed (Campana, 2001). The state of the otolith edge (opaque or translucent) pooled across all age classes was also examined to compare with MIA. As discussed by Campana (2001) each age class should ideally be validated for annuli formation, however due to the low frequency of fish present in age classes over 4, only ages 1, 2, 3 and 4 were examined. Each showed a similar trend so therefore age classes were pooled in the age ranges explained above.

A re-read of 200 randomly selected otoliths across the observed age structure was completed to determine the precision of annuli counts and calculate a coefficient of variation (CV) for the duplicate counts (Campana, 2001). CV was calculated as the average of the multiple reads divided by the standard deviation of the same range and expressed as a percentage. An age-bias plot was also fitted to determine any under- or over-aging of the re-read sample. A reference collection determined by three readers was read before the start of age estimation to ensure consistency between reads and to train ageing the species.

4.2.4 Growth and longevity

Growth rates were modelled using the von Bertalanffy Growth Function (VBGF) and fitted to length-at-age data for both males and females and combined using the equation:

$$L_t = L_\infty . (1 - e^{-k(t - t_0)})$$

where L_t is the fork length (cm) at age t, L_∞ is the asymptotic fork length (cm), k is the rate at which the function approaches L_∞, and t_0 is the theoretical age (years) at length zero. The growth function was fitted using a nonlinear least squares routine in SOLVER in Microsoft Excel (Haddon, 2011). The pooled results are important to provide information for the state-wide management of the stock as a whole. The null hypotheses of no difference in growth between males and females, and between the north and south regions were tested using residual sums of squares methods (ARSS) as outlined by Chen *et al.*, (1992), over similar size and age ranges. The midpoint of age classes was used for the analysis of growth as it reflects the range that a fish may be, due to the protracted spawning season of the species.

4.2.5 Length and age composition

The *A. aequidens* length frequencies collected as part of the NSW fish monitoring program were weighted to commercial landings during the sampling period. This was completed using an internal departmental program (Pisces), where the length frequencies collected from a region are weighted to reflect differences in commercial landings between regions (i.e. lengths collected from a region that had higher landings are weighted to carry more proportion of length distributions). The south region was only weighted using commercial landings from Forster due to low sampling of lengths from other minor ports of landings for *A. aequidens* (e.g. Newcastle and Sydney). The north region length frequencies were weighted by all locations within the sampling region where length data were collected. Weighted length distributions were compared using a Kolmogorov-Smirnov (KS) test to test the null hypothesis of no difference in the length-frequency distributions between the north and south regions (IBM SPSS Statistics for Windows Version 22.0).

Age distributions are an important stock assessment tool providing estimates of mortality rates, fishery recruitment and strong/weak year classes. To ensure age distributions determined from the samples reflected as closely as possible the age composition of the NSW commercial fishery, the age distribution of biological samples of *A. aequidens* were used to create an age-length key. This was based on fish greater than the minimum legal length of 38 cm TL (i.e. approximately 35-36 cm FL). Using the weighted length frequency data and the age-length key, age proportions were calculated using the method of Kimura (1977). Age-length keys and age proportions were constructed for the NSW fishery as a whole and separately for each north and south region.

Recreational catches were sampled at handline fishing competitions mainly from the north region, Evans Head. No additional recreational length frequency data were collected so only the raw age distribution data are presented (n=151).

4.2.6 Mortality estimates

Estimated age distributions were used to generate mortality estimates of the commercial fishery of *A. aequidens* in NSW. Instantaneous total mortality (Z) estimates were calculated by fitting a regression to the natural logarithm of abundance (% frequency of proportion) at age for the fully recruited age classes to calculate the slope of the descending limb of the catch curve (Ricker, 1975). Natural mortality (M) was estimated by the method outlined in Then *et al.*, (2014) for exploited populations based on the maximum observed age using the equation: M=4.899 ($t_{max}^{-0.916}$), where t_{max} is the maximum observed age during the sampling period i.e. 14 yr. Fishing mortality (F) was then estimated by subtracting M from Z.

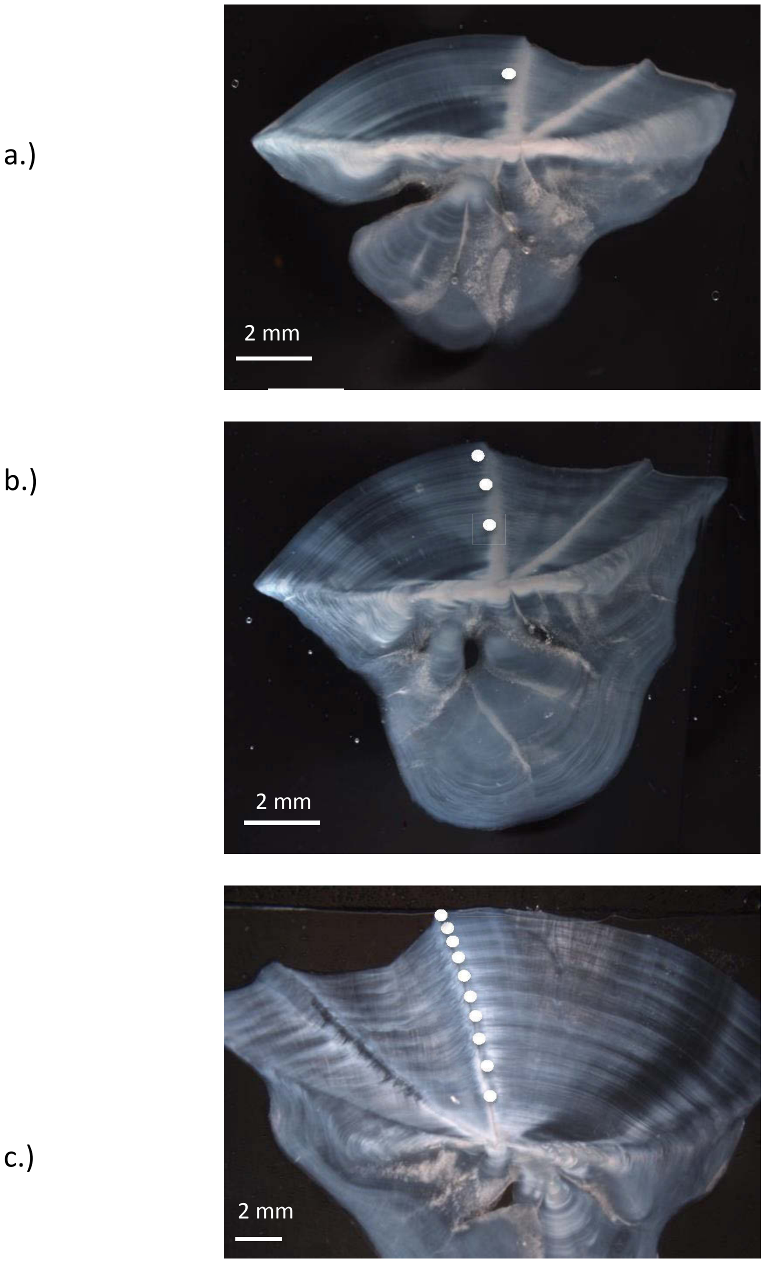


Figure 4.2. Sectioned otoliths of *Atractoscion aequidens* viewed using reflected light at x2 magnification a.) 51.8 cm FL Female age 1, b): 63.4 cm FL Female age 3, c): 77.5 cm FL female age 10.

4.3 Results

4.3.1 Otolith processing and age estimation

A total of 1,490 fish were processed for otolith-based age estimation and age estimates ranged from 0 to 14 yr. Commercially caught fish were between 34-86.2 cm FL, with the majority (74%) of fish sampled between 35 and 56 cm FL. Females sampled were on average 46.6 cm FL in the north region and 44.5 cm FL in the south region (Table 4.1.). Mean length of males sampled in the north was 43.7 cm FL and in the south 43.6 cm FL. The oldest fish sampled was a 14 yr old male (77 cm FL) from Coffs Harbour. Fish smaller than the MLL caught on permit ranged in size from 9 cm TL (fork length not differentiated at this size) to 33 cm FL. A larger number of samples came from the south region due to easier access to catches at the fishermen's co-operative. Sex ratios were significantly different (see Chapter 3).

Sectioned sagittal otoliths of *A. aequidens* were viewed under reflected light and characterized by a dense opaque core surrounded by a very wide opaque zone, marked as the first annuli (Figure 4.2.a). Opaque bands became subsequently narrower with a pattern of alternating translucent zones (Figure 4.2.b, c). As fish grew (> 2 yr), the pattern of translucent and opaque zones became more discernable (Figure 4.2.c).

There was 85% agreement when a sample of otoliths was re-aged (n=200; CV=9.7%). The maximum difference for the other 15% was ± 1 annuli count. Of those fish, 80% were 1 or 2 yr of age which demonstrates the difficulty of ageing young fish and was often due to the difficulty of assigning the edge type. An age-bias plot indicated no bias towards under- or over-ageing (Figure 4.3.)

Table 4.1. Fork length (FL, in cm) of *Atractoscion aequidens* from the north and south regions. Data by regions is pooled for all male and females sampled in the region. Rec frames are *Atractoscion aequidens* caught by recreational anglers.

Region/ Sample	Mean FL (±SE)	Min FL	Max FL	N
North	45.7 (0.4)			559
Female	46.6 (0.6)	31.1	86.2	325
Male	43.7 (0.5)	29.6	77.0	206
Rec frames	49.9 (1.6)	38.0	68.8	28
South	43.5 (0.3)			931
Female	44.5 (0.4)	9	84.7	601
Male	43.6 (0.5)	24.2	70.3	268
Rec frames	50.4 (2.0)	26.4	61.2	22
			Total	1490

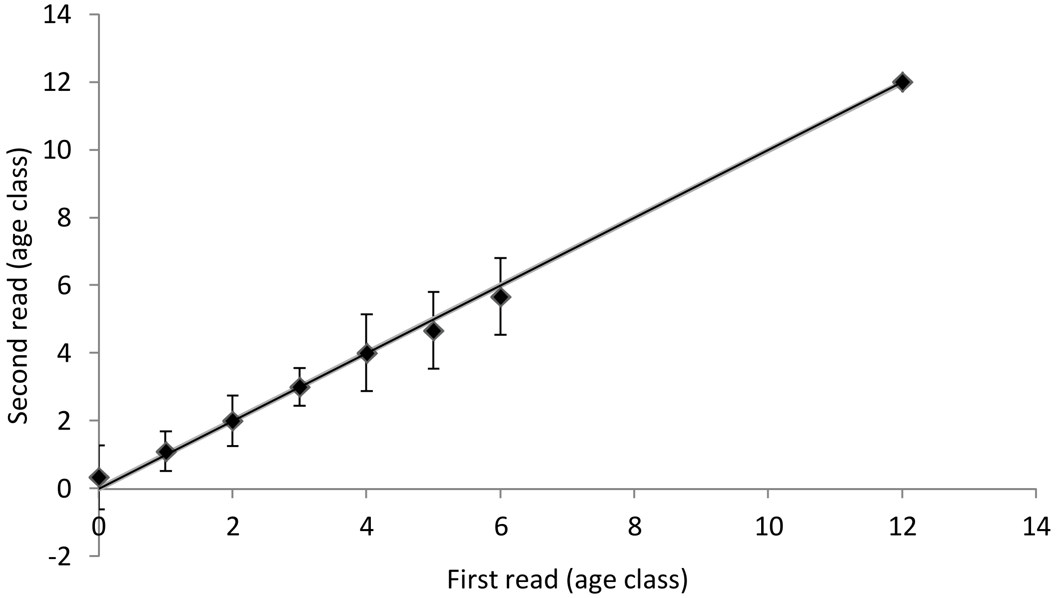


Figure 4.3. Age-bias plot of *Atractoscion aequidens* comparing mean (±SE) first age count against mean re-read.

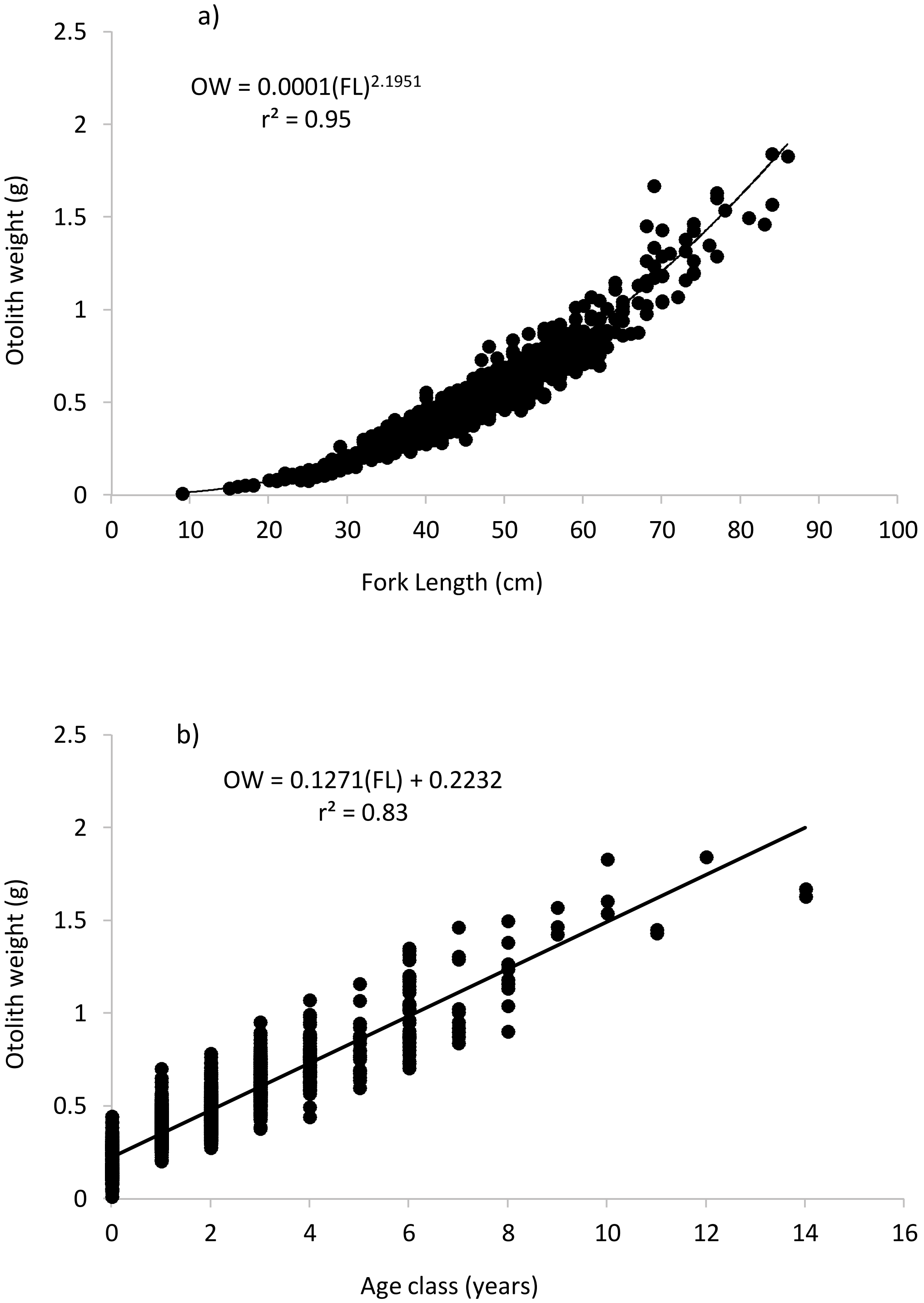


Figure 4.4. Relationship between a) fork length (cm) and otolith weight (g) and b) age class and otolith weight (g). n=1,468 (outliers removed).

Single sagittal otoliths of *A. aequidens* ranged in weight from 0.01 g for a 9 cm TL fish to 1.8 g for the largest fish sampled, 84.7 cm FL female. The relationship between otolith weight (OW) and FL was best described by the power relationship $OW = 0.0001(FL)^{2.1951}$ ($r^2=0.95$; Figure 4.4.a), indicating continued growth of the otolith throughout the life of the fish. The relationship between age class and OW was best described by the linear relationship $OW=0.1271(FL) + 0.2232$ ($r^2=0.83$; Figure 4.4.b) also demonstrating that increasing numbers of opaque zones were laid down with ageing.

4.3.2 Marginal increment analysis

MIA was plotted by mean MI (±S.E) and month for age classes 1-2 and age classes 3-14 (Figure 4.5.). For the two groups of age classes plotted, mean MI increased and decreased once during the year indicating opaque zones were formed annually and therefore can be used to estimate total age in years. For both groups of age classes, mean MI was highest between September and January indicating austral spring-summer opaque ring formation. There was considerable variation in the timing of mean MI for fish in age-classes 3-14 but this may be due to small sample numbers in some months ($n < 20$ January, August and October).

Edge state (Figure 4.6.) supported the occurrence of opaque zone formation between August and January, with 70-85% of otoliths marked with an opaque edge between these months. Between March–July approximately 60% of otolith edges were translucent, which corresponds to the decrease found in mean marginal increment values.

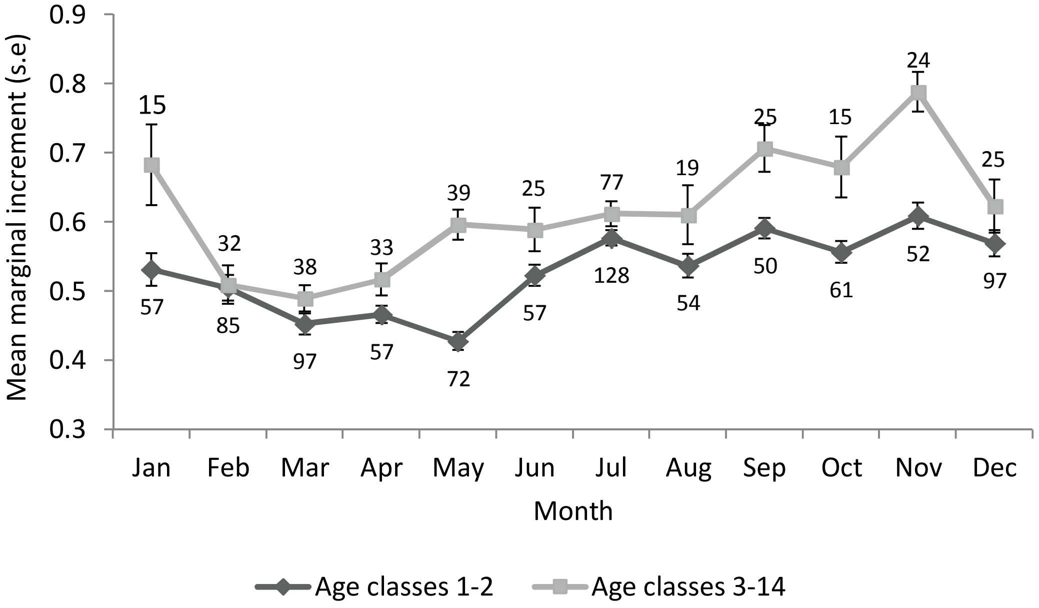


Figure 4.5. Mean marginal increments (±S.E) for *Atractoscion aequidens* age class 1-2 (n=867), and age class 3 -14 (n=367).

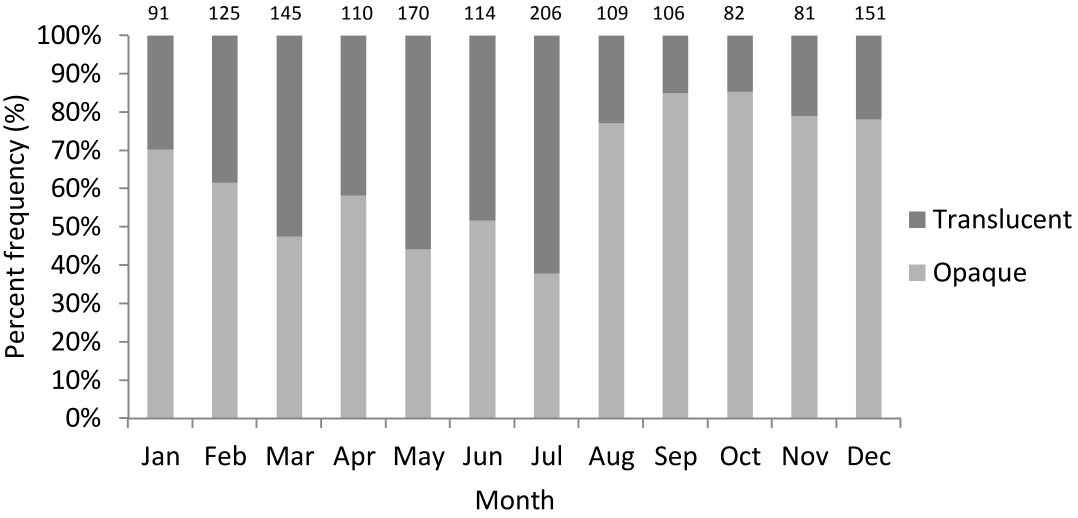


Figure 4.6. Frequency of otolith edge states for *Atractoscion aequidens* (n=1,490) in each month, pooled by sex and region.

4.3.3 Growth and longevity

Growth of males and females differed significantly across all sampling locations (ARSS, $F_{3,\,1400}$ =33.6, P<0.0001; Figure 4.7.a). Fitted VBGF growth parameters indicated that, on average, females grew to a larger maximum size (L_∞=84.6 cm FL), than males (L_∞=69.0 cm FL; Table 4.2.). Growth was similar between sexes for the first 2 yr with males reaching 40.7, 44.6 cm FL and females 42.6, 46.1 cm FL at age 1 and 2 respectively. From 3 yr old mean size-at-age indicated faster growth in females than males (Figure 4.8.a). Mean size-at-age data shows large differences in the average size-at-age from 6 yr between males (55.3 cm) and females (67.1 cm), however only a small number of males over the age of 6 (n=32) were sampled. Size-at-age data were fitted for all fish included in the study (including juveniles; Table 4.2.). Growth was fast reaching 42 cm by age 2 and L_∞ was 73.8 cm FL.

Growth rates differed significantly between the north and south regions (ARSS, $F_{3,\,1317}$ =41.5, P<0.001; Figure 4.7.b, Table 4.2.). Mean size-at-age data for the north and south (Figure 4.8.b) indicated that fish in the north were on average smaller than those in the south: at 2 yr fish were 43.7 cm (± 0.3) in the north and 47.4 (± 0.3) in the south. There was a higher occurrence of older fish in the north than in the south. From age 6, the north region fish had a large variance in the size at age ranging from 45 to 81 cm FL for 6 yr.

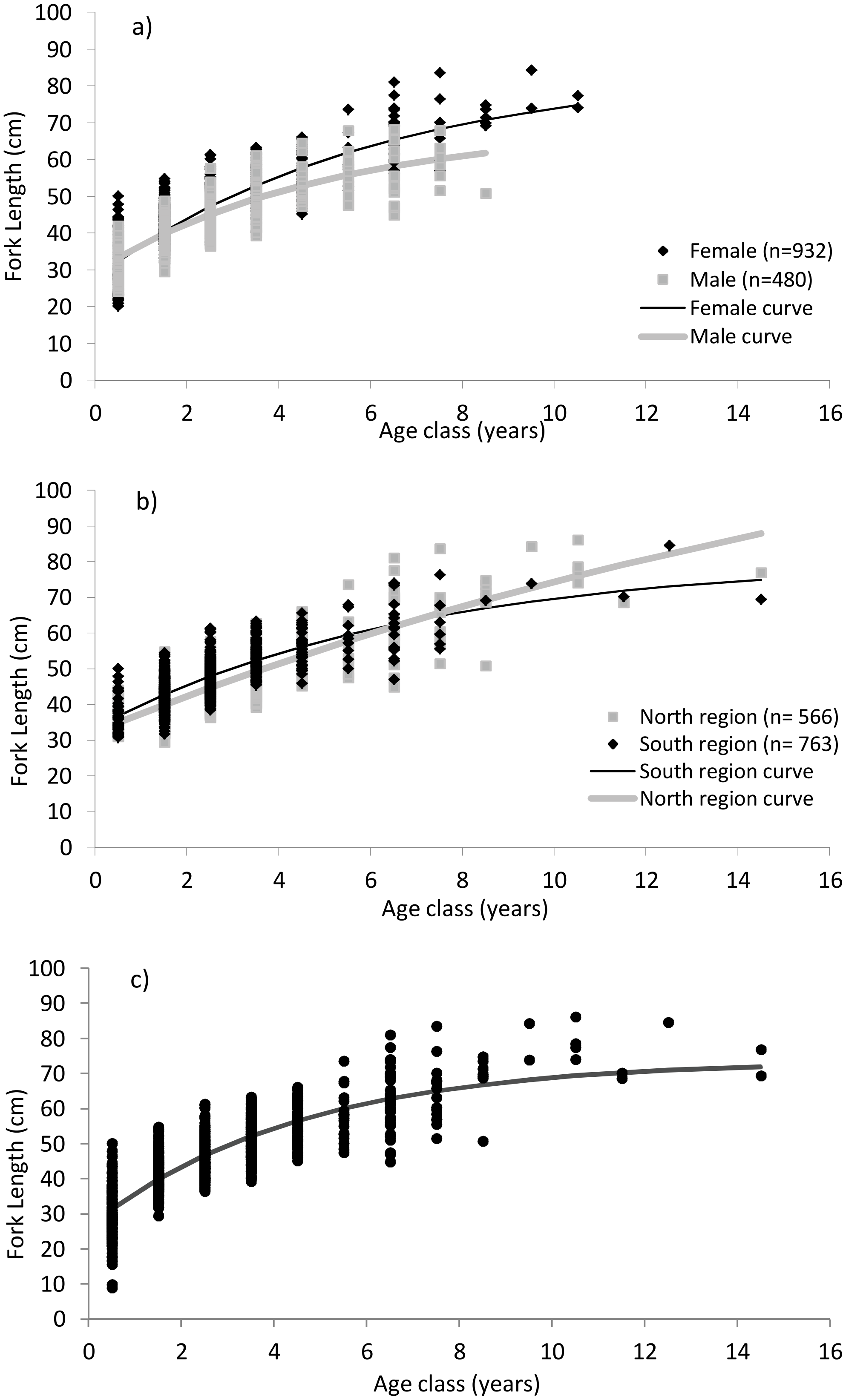


Figure 4.7. von Bertalanffy growth function fitted to a) males and females, b) north and south and c) pooled length at age data for *Atractoscion aequidens* in NSW.

Table 4.2. *Atractoscion aequidens* growth parameters generated from von Bertalanffy growth function.

	L_∞	k	t_0
Female	84.6	0.2	-2.4
Male	69	0.2	-2.8
Combined	73.8	0.2	-1.9
South	80.6	0.2	-3.7
North	148.2	0.1	-5.5

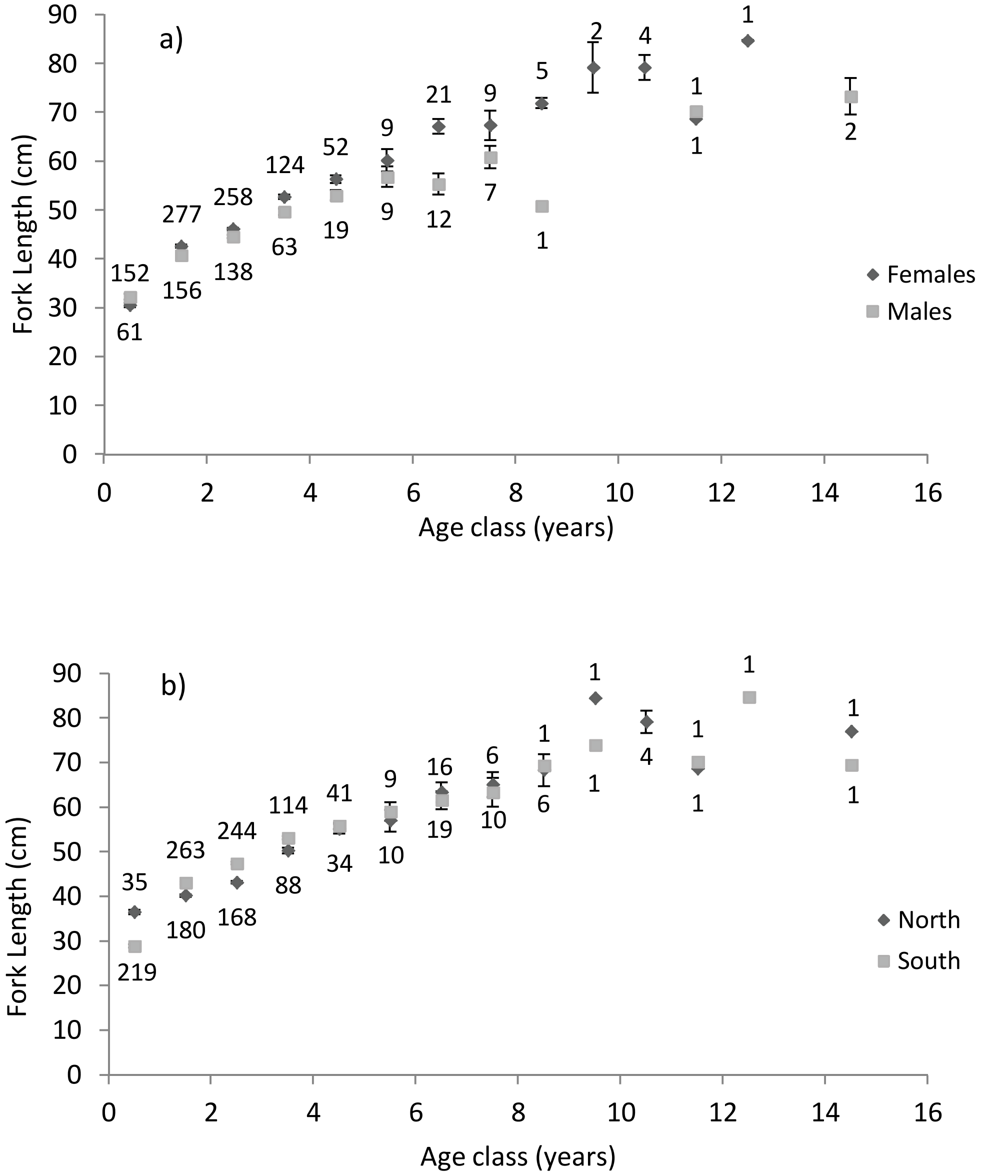


Figure 4.8. Mean size-at-age of a) males and females, and b) north and south *Atractoscion aequidens* in NSW.

4.3.4 Length and age composition

Weighted length frequencies of commercial landings of *A. aequidens* during the sampling period when biological samples were collected (January 2011-June 2012) showed significantly different length distributions (D=0.2586, *P*<0.05, Figure 4.9.). In the north region there was a higher proportion of smaller fish between 35 and 46 cm FL compared to the south region where fish were most commonly between 43 and 53 cm FL. There was a higher proportion of fish over 60 cm FL from in the north (1.7%) compared to the south region (0.5%). In addition, there were more length classes in the north, reaching 87 cm, while in the south the largest length class was 68 cm FL.

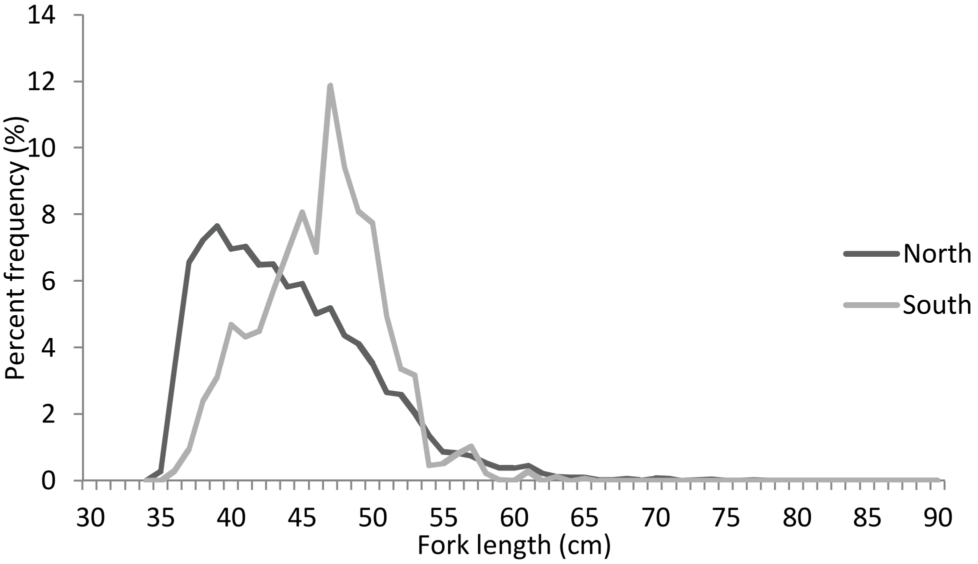


Figure 4.9. Length frequency distributions from the north (n=5,490 and south (n=1,803) regions of *Atractoscion aequidens* collected from the long-term monitoring program run by Fisheries NSW.

Age classes of fish sampled ranged from less than 1 to 14 yr. The estimated age distribution of *A. aequidens* indicated the NSW commercial fishery is dominated by fish aged 1 (35%) and 2 (37%) (Figure 4.10. a). The next most abundant age class was 3 yr (16%). Few fish over the age of 5 yr were sampled (3%). The estimated age distributions between the north and south regions were similar, dominated by age classes 1 and 2 (Figure 4.10.b and c; 71% north, 82% south). The north region had a higher proportion of fish aged 3 and 4 (25%) compared to the south (17%). There were also more age classes found in the north compared to the south. The oldest estimated age class in the south was 7 yr, compared to 14 yr in the north.

The recreational fishery also had a high proportion of fish aged under 3 (82%, Figure 4.10.d) with the dominant age class being 2 yr (37%), followed by age 1 (23%). The oldest age class was 8 yr and only 9% of the raw age distribution was over 5 yr.

Table 4.3. Age-length key for *Atractoscion aequidens* pooled by locations for fish sampled between January 2011 and June 2012.

	Age class															
Length class (FL, cm)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Total
5-9	1															1
10-14																0
15-19	4															4
20-24	32															32
25-29	116	1														117
30-34	55															55
35-39	33	131	45	1												210
40-44	11	194	148	20												373
45-49	2	89	146	55	11	2	3									308
50-54	1	14	68	68	28	4	3	1	1							188
55-59			9	44	18	8	8	5								92
60-64			5	15	15	2	8	2								47
65-69					4	2	4	5	2			1			1	19
70-74						1	7	1	4	1	1	1				16
75-79							1	1			2				1	5
80-84							1	1		1			1			4
85-89											1					1
Total	255	429	421	203	76	19	35	16	7	2	4	2	1		2	1472

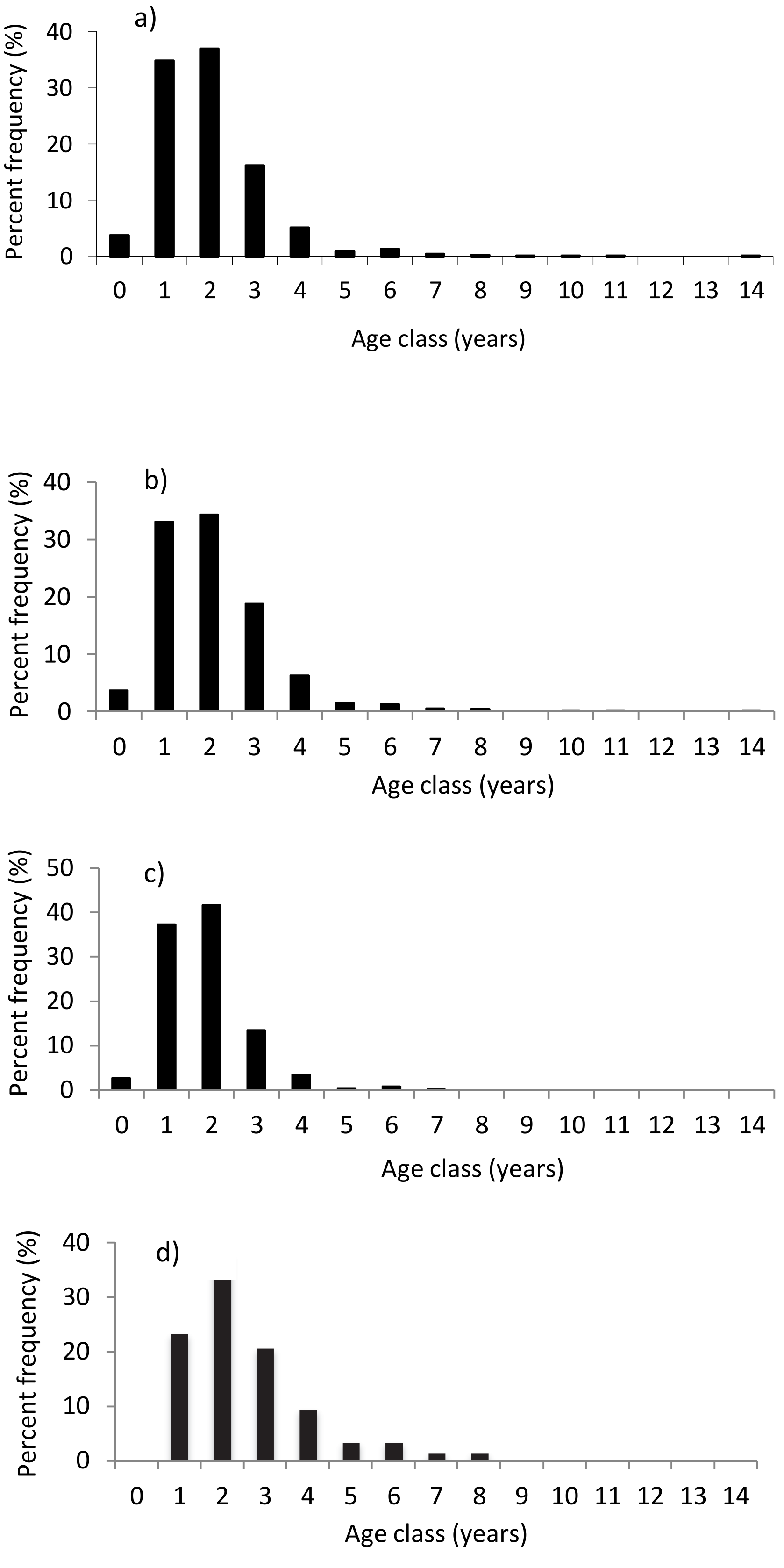


Figure 4.10. Estimated age distributions derived from the age-length key for commercially caught *Atractoscion aequidens* in NSW a.) pooled, b.) north and c.) south. d) Age composition of samples from the recreational fishery (recreational catch is raw proportions only, n=151).

4.3.5 Mortality estimates

Catch curve analysis was used to determine the instantaneous total mortality rate from the south, north and combined based on estimated age distributions for the NSW commercial fishery (Figure 4.11.; Table 4.4.). Age 2 was chosen as the age that fish were fully recruited into the fishery. Age 8 was the maximum chosen as too few fish were sampled beyond this (Age 7 was the maximum estimated age class found for the south). Natural mortality was based on the results from Then *et al.*, (2014) of 0.44 based on a t_{max} of 14, the maximum observed age sampled during the study.

Estimated fishing mortality was higher in the south (0.69) while the north was lower (0.35). The combined fishing mortality was 0.42, very similar to the estimated natural mortality of 0.44.

Table 4.4. Mortality rates based on estimated age distributions of *Atractoscion aequidens* in the NSW commercial fishery.

Region	Age range	*Z*	*M*	*F*
Combined	2 to 8	0.85	0.44	0.42
South	2 to 7	1.13	0.44	0.69
North	2 to 8	0.78	0.44	0.35

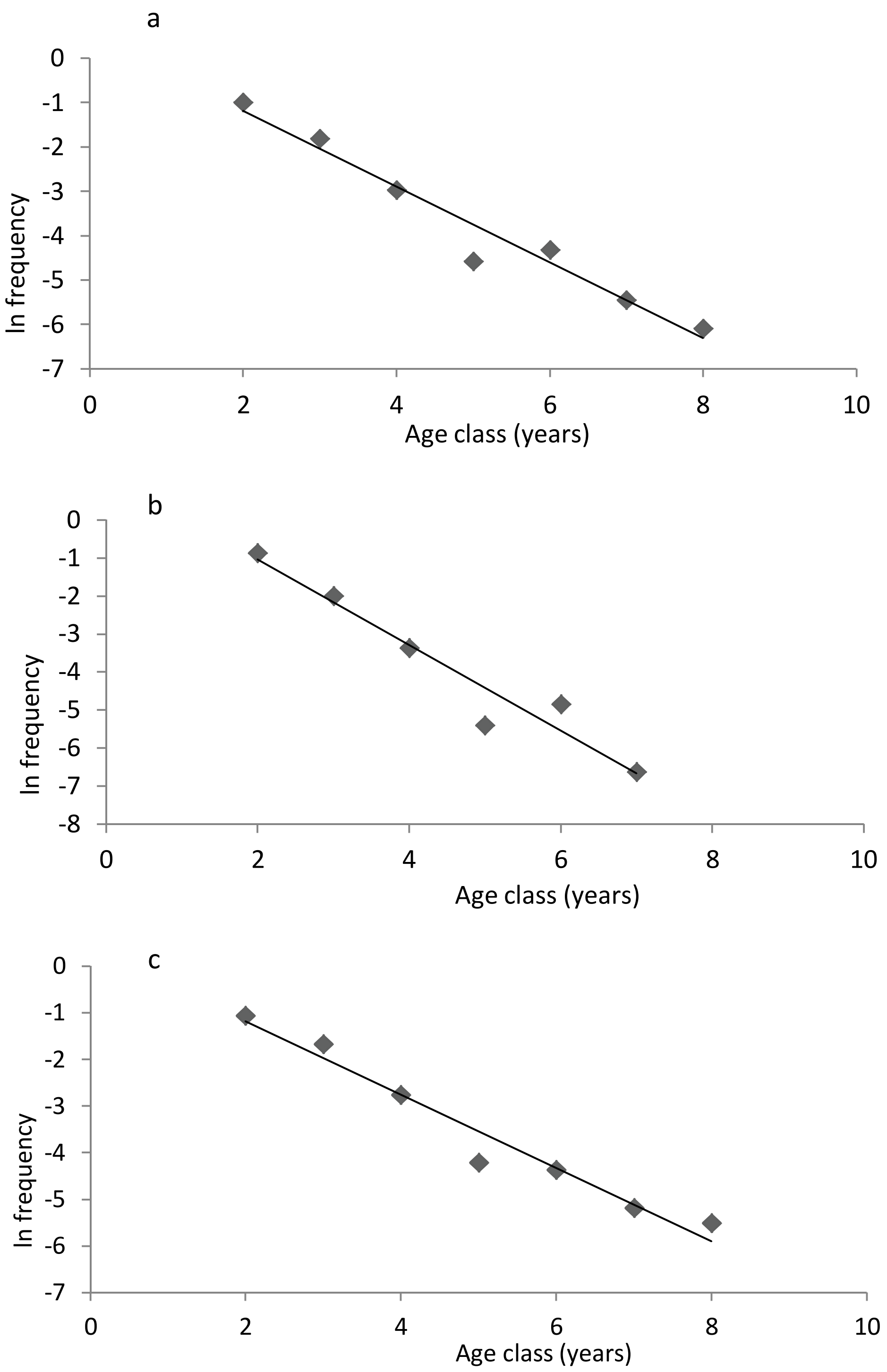


Figure 4.11. Catch curves of *Atractoscion aequidens* in NSW a.) pooled, b.) south and c.) north.

4.4 Discussion

4.4.1 Age estimation and marginal increment analysis

The sagittal otolith of *A. aequidens* was typical of sciaenid otoliths in being extremely large, which is also a common trait in sound producing fish (Chao, 2002; Aguirre, 2003; Helfman *et al*., 2009). Annuli were only visible by sectioning and opaques were wide, interspersed with thin translucent zones. This pattern was found for the other sciaenid in NSW, *A. japonicus* (Silberschneider and Gray, 2005) and *A. aequidens* in QLD (Sumpton *et al.,* 2013). The opposite pattern was found for the congeneric *A. nobilis* (Romo-Curiel *et al.,* 2015) and other sciaenids in the northern hemisphere, where annuli appear as wide and translucent followed by thin opaque zones (*Cynoscion regalis,* Lowerre-Barbieri, *et al.,* 1994; *Micropogonias furnieri*, Borthagaray *et al.,* 2011).

Annual periodicity of opaque zones was validated by MIA, indicating opaque zones were generally laid down during September-January, equivalent to the austral spring-summer. The growth and subsequent annuli formation in temperate fish typically follows a seasonal cycle of being faster in summer (warmer water, increased food availability) and slower in winter (decreased water temperature, reduced food availability) (Moreau, 1987). A similar periodicity was found for *A. aequidens* in QLD (Sumpton *et al*., 2013) and other temperate species off the coast of NSW (e.g. *Trachurus novaezelandiae, Scomber australasicus*, Stewart *et al*., 1999; *Arripis trutta,* Hughes*,* 2012). Annuli periodicity was supported by the edge state analysis, with over 70% of otoliths marked as an opaque edge during the same spring-summer period. Annual opaque zone formation has been validated in numerous species of sciaenid (*Sciaenops ocellatus*, Ross and Stevens, 1995; *Cynoscion regalis,* Lowerre-Barbieri, 1994; *Macrodon atricauda*, Cardoso and Haimovici, 2011).

While MIA is the most widely used validation method for opaque zone formation periodicity it is not without limitations. There are many factors that explain the variability in assigning an edge state including angle of the section, curvature of the otolith, and the light reflection when viewing under the microscope (Campana, 2001). Great care was taken to ensure consistency in edge state determination and hence opaque zone formation. Due to the very fast early growth of *A. aequidens* in NSW (to ~40 cm FL by 1 yr), the first two annuli were very wide compared to subsequent age classes (>3 yr) where growth slowed. Under-estimating ages of fish can result in inferring faster than actual growth rates and lower natural mortality estimates (Campana, 2001). In addition, Francis *et al*., (1992) found that opaque zones may not be completely visible until subsequent material has been laid down outside them. This can result in fish from the same age class being assigned to different age classes (Stewart *et al*., 1999).

Age precision was relatively favourable with mean CV (9.7%) within adequate reference points (Campana 2001). It was similar to that of the CV for age estimates of the congeneric *A. nobilis (*11.5% in Romo-Curiel *et al.,* 2015). The vast majority of differences in opaque counts for *A. aequidens* were for fish 2 yr and under (80%), a similar result to age estimation for *A. nobilis* (Romo-Curiel *et al.,* 2015). Other species of sciaenid (such as *C. regalis*) have exhibited a high precision in otolith readability. This species, like *A. japonicus* in NSW, is euryhaline, moving between the estuary and offshore, resulting in more defined opaque/translucent zone formation due to large changes in temperature between the estuaries and ocean (Lowerre-Barbieri, 1994). The fact that *A. aequidens* is completely marine, has very rapid growth in the first few years, and has a protracted spawning season, explains the higher CV score than the average found for other teleosts of 7.7% (Campana, 2001).

While many ageing studies use otoliths of young-of-the-year fish to validate the age of formation of the first ring by counting daily rings (Campana, 2001), this was precluded for *A. aequidens* due to the fact the species has a protracted spawning season which would be of no benefit in determining the true age of the first ring (see Chapter 3) i.e. the first ring could be any number of days old depending on when the fish spawned in relation to time of year of opaque zone formation.

4.4.2 Growth and longevity

The VBGF growth function provided an adequate fit to the size-at-age data for *A. aequidens* in NSW describing the growth for females (r^2=0.74), males (r^2=0.69) and overall (r^2=0.73). Extremely rapid growth to ~40 cm FL by 1 yr was comparable to both *A. aequidens* in QLD (Sumpton *et al.,* 2013) and the much larger conspecific in South Africa (Griffiths and Hecht, 1995a) and to the other sciaenid in NSW, *A. japonicus* (Silberschneider and Gray, 2005).

There was a significant difference in growth rates between male and female *A. aequidens* in NSW, with females (L_∞=84.6 cm FL) reaching a larger asymptotic length than males (L_∞=69.0 cm FL). This result is typical of other closely related sciaenids (Griffiths and Hecht 1995a; Lowerre-Barbieri *et al*., 1996; Bortone 2003; Silberschneider and Gray, 2005; Farmer *et al.,* 2005; Hutchings *et al.,* 2006; Gonzalez-Quiros *et al.,* 2011). Female body size is positively correlated to fecundity for this species (see Chapter 3) highlighting the importance of older, larger fish in the population as female reproductive success increases with length and with age (Hutchings, 2000; Berkeley *et al*., 2004; Green, 2008). On average, males were slower growing in all age classes compared to females with a marked divergence from age 6. By comparison, growth of male and female *A. aequidens* in South Africa did not differ (Griffiths and Hecht, 1995a).

Interestingly no difference in growth rates between males and females was found in QLD even though NSW is in close proximity (Gold Coast, QLD to Coffs Harbour, NSW ~ 250 km). The modelled asymptotic length was also much smaller in QLD ($L\infty$=62. 6 cm; Sumpton *et al*., 2013), however the majority of the samples collected were from the inshore charter-boat fishery. The QLD study found that size frequencies of *A. aequidens* may be depth-related with commercial fishers landing larger fish than those from the inshore charter-boat fishery (Sumpton *et al*., 2013). Differences in estimated asymptotic growth may be due to the counter-gradient growth theory, which predicts that maximum size and asymptotic length increase with distance from the equator and has been demonstrated for numerous reef-fishes (Choat *et al*., 2003; Robertson *et al*., 2005) and for the sciaenid *C. regalis* (Lowerre-

Barbieri *et al.*, 1995). Growth rates maintained the initial trajectory and slowed upon reaching maturity (~35 cm FL, age ~ 1 yr), much smaller than where growth slowed for *A. japonicus* in NSW and other sciaenids (e.g. *Sciaenops ocellatus*; Porch *et al.*, 2002). Growth was similar between the sexes until 1 yr where growth diverged and females grew at a faster rate. This age corresponds to the age that 50% of the samples reached sexual maturity (see Chapter 3). A common life history trait amongst teleosts is for growth to slow after reaching sexual maturity (Stewart and Hughes, 2007; Walsh *et al.,* 2010; Folkvord *et al*., 2014; Stocks *et al.,* 2014;), which was the case for *A. aequidens* in South Africa where growth slowed at 90 cm FL and 5 yr (Griffiths and Hecht, 1995a). Similarly, in *A. japonicus* in NSW growth was similar between males and females until females reached sexual maturity after which females grew faster and attained greater lengths (Silberschneider *et al*., 2009).

For both sciaenids found in NSW, early growth rates are comparable to their conspecific counterparts in South Africa, reaching ~40 cm within 1 yr. While growth rates are similar, both *A. japonicus* and *A. aequidens* attain much larger size and age in South Africa (*A. aequidens* 130 cm TL, 25kg ; *A. japonicus* 181cm TL, 42 yr) than in NSW (*A. aequidens* 100 cm TL, 10kg ; *A. japonicus* 132 cm TL, 24 yr) (Griffiths and Hecht, 1995b; Silberschneider *et al*., 2009).

The oceanic waters surrounding South Africa are highly productive supporting a large fish biomass in the southern Benguela current region (Blamey *et al*., 2016) and support larger sized fish compared to that in NSW. The Benguela current is a northward flowing current and is one of the world's major coastal upwelling systems with cold, nutrient rich and productive waters (Lutjeharms and Meeuwis, 1987). While the EAC does give rise to some productive upwellings, EAC waters are poleward flowing and bring warmer, less nutrient rich waters to the NSW coastline. The fisheries in South Africa are much larger than in NSW reflecting the productivity of the region (DAFF, 2014; Stewart *et al*., 2015).

The large differences in biology of *A. aequidens* between Africa and NSW may be attributable to the two areas representing different populations. Henriques *et al*., (2014) studied the genetic differences between *A. aequidens* from South Africa with the same species off the coast of Angola. They found the populations were distinct with no interbreeding occurring due to the isolating effects of the cold water system of the Benguela Current. It is believed sections of the current act as a barrier to larval dispersal and gene flow between the two populations. From unpublished data (W. Potts cited unpublished in Henriques *et al*., 2014), the species off Angola was found to reach sexual maturity at approximately 2 yr and attain a much smaller maximum size than the population found off South Africa. Henrique *et al*., (2014) believe the large differences in *A. aequidens* life history characteristics between the two regions is due to the divergent life histories being matched to the surrounding oceanographic conditions. The South African population displays a highly migratory spawning behaviour over a short time frame (3 mo, Griffiths and Hect, 1995) with larval dispersal occurring in the Agullhas Current System. A similar pattern of spawning migration was not found for *A. aequidens* off the coast of Angola (unpublished W.Potts), where the species has a much longer spawning period (~ 7 mos) and smaller length at maturity. Henrique *et al*. (2014) surmise that the extended spawning season is to ensure eggs are distributed widely by bi-directional currents. Further they believe the life history characteristics have evolved in response to the two differing oceanographic conditions to enhance larval dispersal and survival in the unstable boundary environments of the Benguela Current system.

The population genetic divergence (Henrique *et al*., 2014) values for the two regions were very high reflecting the presence of an impermeable barrier between the two regions. A spawning migration was not found for *A. aequidens* in QLD (Sumpton *et al*., 2013) or in the current study. The larger body size found for the South Africa population is consistent with other observations that species migrating to form spawning aggregations are typically larger (Roff, 1988; Claydon, 2004). This may also explain the delay in maturity as energy is directed to attaining a large body size and away from reproductive output until that size has been attained. While it was initially suspected *A. aequidens* in South Africa may be a different species due to the significantly different life history parameters, the biology of the Angolan population is very similar to the NSW stock. This suggests that like the Angolan population, *A. aequidens* in NSW has a suite of life history characteristic suited to its environment with the EAC playing a key role in larval dispersal, as has been found for many species on the east coast of Australia (Ridgway and Dunn, 2003).

Length-at-age data were highly variable for *A. aequidens* with ranges up to 40 cm FL within an age class however the fit to the VBGF growth model was good. This was also found for *A. nobilis* with a range of length-at-age up to 50 cm (Romo-Curiel *et al.,* 2015), however this species grows to a considerably larger length than *A. aequidens* in NSW. An almost-year-round spawning season (see Chapter 3) may account for this variability in size-at-age for *A. aequidens*. Fish born at different times of the year experience a range of different environmental conditions (temperature, prey availability), which can affect growth and mortality rates; warmer water is generally positively correlated with faster growth (Lowerre-Barbieri *et al*., 1995; Thresher *et al*., 2007; Stocks *et al*., 2011; Gillanders *et al*., 2012; Rountrey *et al*., 2014). In addition high variability in size-at-age may also be due to elevated growth rates in pre-mature fish, which was found for *A. aequidens* in South Africa and the sciaenid *Micropogonias undulatus* (Atlantic Croaker, Lowerre-Barbieri *et al*. 1994).

4.4.3 Length and age composition

Weighted commercial length-frequency distributions showed that fish were larger in the south region than the north. There was a higher proportion (60%) of smaller (34 – 45 cm FL) fish in the north, compared to the south (41%). There was a higher proportion of fish greater than 55 cm FL in the north (5%) than the south (3%), plus a much larger length range. The largest estimated length based on the ALK was 68 cm FL in the south, much smaller than the largest estimated length in the north of 87 cm FL. The south region length frequency distribution showed some pulses of fish at 40, 45, 47 and 57 cm FL. The north showed strong recruitment into the fishery at the size of the MLL 35 cm FL (38 cm TL).

While fish were generally larger in the south, age distributions indicated a maximum age class of only 7 yr compared to 11 yr in the north. There was a higher proportion of fish under 1 and 2 yr in the south (82%) compared to the north (71%). These results suggest fish are faster growing in the south region, reaching larger sizes than the north. A higher proportion of older, slower growing fish was found in QLD, which is the northern extent of the species range off the east coast of Australia. This was also supported by the fact that there is a higher proportion of older but smaller fish in the north region compared to the south in NSW. The fact that fish are larger but younger in the south may be a linked to the EAC producing upwelling with greater food availability and nutrients resulting in faster growth in the south. Food availability has been found to have a greater influence on fish growth than temperature (Neat *et al.*, 2008; Hernandez-Miranda and Ojeda, 2006).

The fact that the commercial age distribution is based primarily on young fish of 1 and 2 yr (pooled 72%) indicates that the fishery is recruitment driven. There have been previous reports of fisheries based primarily on young fish being at greater risk to environmental fluctuations and prone to larger boom and bust cycles than non-exploited fish (Hsieh *et al.*, 2006). However Anderson *et al.*, (2008) found susceptibility of exploited fish stocks is more highly correlated to increased growth rates leading to increased instability. The removal of larger, older fish from a population through fishing, resulting in age truncation or reduced age distributions, leads to unstable population dynamics and explained much of the volatility in exploited fish stocks from analysis of a 50 yr larval fish record in California.

There is strong evidence of cyclical pulses within the NSW commercial fishery (Stewart *et al.*, 2015), which warrants further investigation but was outside the scope of this study. It further supports the notion of a recruitment driven fishery where strong pulses may occur during periods of favourable environmental conditions linked most likely to the El Nino-Southern Oscillation phenomenon (Wells *et al.*, 2006; Gillanders *et al.*, 2012).

The oldest fish sampled within the study period was 14 yr, the same age as the oldest found in QLD (Sumpton *et al.*, 2013). This is older than the maximum age observed in South Africa of 9 yr (Griffiths and Hecht, 1995a). Despite the lack of many older fish in the sampling, the intensity and coverage of the length frequency sampling indicates that the fish sampled are most likely representative of the fish available to the commercial fishery in NSW. While there is risk in fishery-dependant sampling of under-representation of the population, Sumpton *et al.*, (2013) pointed out that the latitudinal range of *A. aequidens* is quite restricted compared to other teleosts found off the east coast of Australia and therefore the sampling done for this study should be representative of the population. However whether that age is indicative of what the maximum age may have been before its decline in abundance is unknown. You would expect the species to have an older maximum age based on the maximum recorded size of the species of 1 m, and in an unfished population.

4.4.4 Mortality estimates

Estimates of fishing mortality for the NSW commercial fishery of *A. aequidens* during the sampling period suggest the fishery is not experiencing overfishing, as initially suspected (Stewart *et al.*, 2015). However, a precautionary view to these results is advisable. The estimated fishing mortality was very high in the south region of Forster, suggesting it is subject to heavy exploitation. Both the north and south region converted age distributions were based almost exclusively on fish under 3 yr and the low abundance of fish in the larger size classes indicates that the fishery is most probably experiencing age truncation. Even though the maximum recorded age during this study was 14 yr, the fishery is still experiencing reduced age distributions with very few fish estimated to be over 5yr (3%). The high exploitation of *A. aequidens* in NSW in the 1950's most probably caused a substantial decrease in *A. aequidens* abundance (Stewart *et al.*, 2015). This is supported by local depletions off Sydney where a large fishery once existed during that period and is now virtually non-existent (see Chapter 2). The decreased abundance may be attributed to very rapid growth during the first few years and a small size and age at sexual maturity. Fishery-induced changes in evolution have been found to result in smaller size and age at maturity for a range of marine species (see review in Jorgensen *et al.*, 2007) and may be slow to reverse or irreversible (Law, 2007). Faster growth increases species' resilience to fishing pressure and there are numerous examples in sciaenid's (*Macrodon atricauda*, Cardoso and Haimovici, 2011). However, faster growth rates have also been said to contribute to instability in population dynamics of exploited stocks (Anderson *et al.*, 2008). Further research on natural mortality for this species is needed.

4.4.5 Conclusion

This was the first study to describe the age and growth parameters of *A. aequidens* in NSW, including growth rates, longevity and estimated mortality rates. The species exhibited rapid growth in the first year, comparable to the species in QLD and the conspecific in South Africa. Fitted VBGF growth parameters indicated females attained a larger asymptotic length than males, a common finding in sciaenids and teleosts. Length-at-age was highly variable, most likely due to the year-round spawning the species exhibits in NSW.

Mortality rates did not indicate high exploitation in the commercial fishery however commercial age compositions indicated the fishery is primarily based on young fish (< 3 yr) and may be recruitment driven. If the fishery is operating at reduced abundance, but not experiencing overfishing, caution still needs to be applied in the management of the NSW stock.

While life history characteristic of *A. aequidens* appear robust (young size-age at maturity, rapid growth, year-round spawning) a conservative approach is paramount to the genetic diversity, range distribution and life history of the species. The age and growth parameters will provide vital baseline data that can be used in future model-based assessments.

Chapter 5: General Discussion

The life history characteristics of a species determine the likelihood of it being exploited sustainably, including its resilience to unpredictable changes in the environment. Without knowledge of growth and mortality rates, age structures, and length/age at maturity there is risk of inadequate management measures resulting in over-exploitation of the stock. This can lead to decreases in abundance (Pauly *et al.*, 2002), increased susceptibility to changes in environmental conditions (Hsieh *et al.*, 2006), potential for genetic bottlenecks (Mirini *et al.*, 2016) and fishery-induced alterations to population dynamics (Jorgensen *et al.*, 2007) that may be irreversible (Law, 1989).

There are numerous examples worldwide, and in Australia, of the long-lasting effects of fishing on marine species (Hutchings, 2000; Levin *et al.*, 2006; Pauly and Zeller, 2016) and especially of declines in stocks of exploited sciaenids (Griffiths, 2000; Chao, 2002; Silberschneider and Gray, 2005; Pondella and Allen, 2008). Fisheries based on species with little or no knowledge of life history characteristics have been reduced for decades with few signs of recovery (*A. japonicus* and *A. aequidens* in South Africa; Griffiths, 2000). However there are sustainable fisheries for many species, where successful management practices have been developed, implemented and enforced with life history information such as fisheries in NSW (*Mugil cephalus*, *Arripis trutta*, *Sarda australis*; Stewart *et al.*, 2015) and globally, such as one of the world's largest cod stocks, *Gadus morhua,* which is at record highs (Vasilakopoulos and Marshall, 2015).

The aim of the current study was to support sustainable fishing of the *A. aequidens* stock in NSW by describing the fishery and investigating relevant aspects of the species' life history and ecology. Despite the relatively long history of exploitation, prior to the current study, no knowledge existed on the life history characteristics of *A. aequidens* in NSW, severely limiting the development of sustainable management strategies. The existence of geographical variation in age, growth, and reproductive characteristics was investigated and compared with information available from southern QLD and South Africa.

This study found differences in the biological parameters of *A. aequidens* between populations in eastern Australia and South Africa, but similarities to populations in Angola and QLD. The current MLL in NSW has been in place since 1940 and not based on any life history information for the species. A study into the life history of the other sciaenid in NSW, *A. japonicus* found the MLL of 40 cm TL to be 30 cm less than the size where 50% of the population reaches maturity, meaning that a large number of fish are landed before they have had a chance to sexually mature and spawn. The collapse and severe depletion of sciaenid stocks in South Africa were due to species being exploited at a rate much higher than the species could naturally replenish (Griffiths, 2000; Sadovy, 2003). The results of this study are central to ensuring the species can be exploited at a rate that promotes the viability of the population. It is envisaged that the improved understanding of this species' life history characteristics will under-pin future assessment and management.

5.1 Reproductive biology

5.1.1 Sex ratios

Sex ratios were skewed to females throughout the study period, with double the number of females sampled to males, despite random sampling of commercial catches. The bias towards females was found both for fish entering the fishery (2 yr) and for undersized fish (<38 cm TL) caught on scientific permit. Skewed ratios may be due to the energy requirements of reproductively active females being higher which was found for sciaenids in South Africa (*U.canariensis,* Hutchings *et al*., 2006; *U. robinsoni*, Hutchings and Griffiths, 2010). This is a plausible explanation in this study, as the species is known for its voracious behaviour on baited handline (Griffiths and Hecht, 1995a; Stewart *et al.,* 2015) and year-round spawning may result in higher female catchability. Differential habit occupation has been another reason put forth for extremely skewed sex ratios where males and females may prefer differing depths, which has been found in other teleosts (Solomon *et al.,* 2011; Macuiane *et al.,* 2009) and sciaenids (Lewis and Fontoura, 2005). Similar skewed sex ratios found in this study have been found in sequential hermaphroditic species (first mature as one sex, change later to the other sex), where protogynous species (first mature as females) are biased towards females (Allsop and West, 2004; Chopelet *et al*., 2009). In South Africa the commercially targeted protogynous sparid, *Chysoblephus puniceus*, was found to have strongly skewed sex ratios towards females. As fishery exploitation increased, the more pronounced the sex ratio skewness, with over 90% of the catch containing females (Garratt, 1985 in Chopelet *et al*., 2009). There is confidence that *A. aequidens* are gonochoristic, so the explanation for heavily skewed sex ratios towards females requires further research.

5.1.2 Spawning period

Based on the analysis of the reproductive biology, in NSW *A. aequidens* is an asynchronous, serial batch spawner with indeterminate fecundity, a common mode of reproduction among sciaenids (Sadovy, 2003; Lowerre-Barbieri *et al*., 2011). A major finding of this study was evidence for year-round spawning of *A. aequidens*. GSI was elevated for most of the year (~ 9 mos) with both males and females displaying a very similar trend of mean GSI increasing and decreasing over the same period. The histological analysis validated the presence of hydrated eggs in macroscopically staged "4" running ripe gonads (Table 2.1), which were present throughout the entire sampling period, even during the 3 mo period when GSI declined. This indicates that spawning is likely to occur year-round with a peak during the austral summer months. While this result was also found in QLD (Sumpton *et al*., 2013) and is similar to that found for the Angolan stock (~7 mo, W. Potts, unpublished data), many closely related sciaenids have a well-defined spawning period, typically of 3-6 months duration (Appendix A). Many other temperate fish species in similar habitats also have defined spawning periods (*Arripis trutta*, Hughes, 2014; *Pagrus auratus*, Stewart *et al*., 2015; *Sarda australis* Stewart *et al*., 2013), including *A. aequidens* in South Africa (Griffiths and Hecht, 1995a).

Histology confirmed the presence of atretic oocytes, which has been linked to periods of poor food availability and changes in water temperature (Hideout *et al*., 2005; Jorgensen *et al.,* 2006). Rates of atresia are important in spawning stock biomass or stock recruitment models. Year-round spawning allows the species to take advantage of periods of optimal environmental conditions and during periods where conditions are less favourable, reabsorption of gonad nutrients may occur. Research determining estimates of the proportion of females undergoing mass or partial atresia would be of great interest, as batch fecundity values may be inflated. A detailed analysis of gonad histology over the course of a year would be required to determine these estimates (Rideout *et al.,* 2005). Determining whether the species partakes in mass or partial atresia may differ year to year, depending on the environmental conditions.

The spawning migration the species undertakes in South Africa takes advantage of the Agulhas current dispersing larvae to nursery grounds. Off the coast of Angola the region is highly variable and a prolonged spawning season ensures a steady supply of eggs to ensure larvae success when conditions are favourable. This spawning season is similar to what was found in NSW, and reflects the similarities in the oceanographic conditions of the Benguela current off Angola and the EAC on the east coast of NSW where both regions are strongly affected by western boundary currents (Ward *et al.*, 2003).

5.1.3 Length/age at maturity

Fast growth with associated early maturation is often a typical finding in fish (Head *et al.*, 2016) and was found for *A. aequidens* in NSW with the length/age at maturity (50%), 36 cm FL and ~ 1 yr. This length is similar to the MLL (38 cm TL) in NSW and to the results found in QLD (35 cm FL, Sumpton *et al.*, 2013) and Angola (2.2 yr, Unpublished W.Potts). The result is dissimilar to what was found for *A. aequidens* in South Africa where length/age at maturity (100%) was 90 cm TL and 5 yr (Griffiths and Hecht, 1995a). This difference in maturity between the populations may be due to the spawning migration that *A. aequidens* undertakes in South Africa, which is not evident for the populations in Australia or Angola. The large size of the South African *A. aequidens* is consistent with the finding that fish that undertake large migratory patterns are typically larger (Roff, 1988; Clardy, 2004).

5.2 Age and growth

5.2.1 Growth rates

Fish have been described as following indeterminate growth patterns, investing resources into growth until maturity is reached (Folkvord *et al.*, 2014). Males and females grew rapidly and at similar rates until reaching sexual maturity after which females grew faster and to larger sizes than males. The modelled asymptotic length for female *A. aequidens* (L_∞= 84.6 cm FL) was similar to the maximum length of females sampled in this study (86 cm FL), but was smaller than the historically reported maximum length of 100 cm (Hutchins and Swainston, 2006). Modelled asymptotic length was smaller for males (L_∞= 69.0 cm FL) and smaller than the maximum length sampled in this study of 77 cm FL. This indicates that *A. aequidens* is capable of growing to a larger size than suggested by the modelled L_∞ estimates. Larger maximum size in females is common among sciaenids (see Appendix A) and found for the species in South Africa (Griffiths and Hecht, 1995a). Female body size is positively correlated to fecundity and highlights the importance of large, older females to the population.

Growth rates between sampling regions in NSW were significantly different, with fish from the south, younger and faster growing than fish from the north where, there was a higher proportion of older, and slower growing fish. This result supports the counter-gradient growth theory which suggests length increases with distance from the equator and has been found in numerous reef fish and the sciaenid *C. regalis* (Lowerre-Barbieri *et al.*, 1997; Choat *et al.*, 2003; Robertson *et al.*, 2005). However further research is required to test this hypothesis as the differences detected may be due to different depths and areas fished by commercial fishermen in each region. In QLD, the size distributions in landings of *A. aequidens* are a result of depth-stratified sampling, where larger fish are from deeper water, and the smaller fish are from inshore.

5.2.2 Commercial age distribution and fishing mortality

The majority of fish sampled during the current study were less than 3 yr (90%) and between 36-50 cm FL (82%). More than 6,000 fish were measured in the NSW commercial monitoring of this species during the sampling period at commercial fishermen's co-ops so there is confidence that the available range of lengths for the species was sampled. However the upper portion of the species length distribution may not have been sampled due to high rates of exploitation meaning fish are not able to grow to larger sizes prior to fishing mortality. The age composition indicates a largely recruitment-based fishery which is dependent upon the abundance of a few early year classes. Estimated age distributions produced from the extensive length frequency collection indicated very few fish over 5 yr (3%) and 60 cm FL (3%).

While the oldest fish sampled in the study was 14 yr, very few fish over 3 yr suggests the commercial fishery of *A. aequidens* in NSW most probably has experienced age truncation. Commercial landings indicating a long-term decline, the maximum age of the fish may be much older. In QLD, they also found evidence of reduced numbers of older and larger fish compared with historical information (Sumpton *et al.*, 2013). Age truncation has been found to increase a species susceptibility to variability in population dynamics and lower its resilience to environmental changes (Beamish *et al.*, 2006; Anderson *et al.*, 2008; Stewart, 2010).

While catch curves show a consistent mortality rate from ages 2 to 8, the stock appears to be under a relatively high fishing pressure which may have led to early maturation, and a dearth of older (>8 yr) fish in the stock. However there is no historical data to compare prior to the expansion of the fishery, observing if the species grew to a larger size (and matured at an older age than at present).

5.3 Management implications

There are many examples of commercial fisheries for closely related sciaenids where current landings are at a fraction of historical catches, including in South Africa (e.g. *A. aequidens*, *A. japonicus* in South Africa (Griffiths and Hecht, 1995a, 1995b) in NSW (Stewart *et al.,* 2015), and in California (*A. nobilis*, Williams *et al*., 2015). The exploitation of these species preceded knowledge of life history characteristics. Subsequent high fishing morality resulted in declines and implementing management can be a challenge to allow rebuilding of stocks (Pauly, 2002).

The NSW commercial fishery for *A. aequidens* likely faces the same challenge. Commercial landings in 2013/14 were 33 t, 15% of the historical high of 215 t in 1956/57 (Stewart *et al.,* 2015). The age composition of the commercial fishery has very few fish over 8 yr, and it is the older and larger fish that are known to be more fecund with more resilient larvae (Berkeley *et al*., 2004; Green, 2008). The commercial landings for *A. aequidens* in NSW have been declining for almost 60 yr with cyclical periods of increased abundance, suggesting a fishery with episodic recruitment. The "buffering" or resilience of *A. aequidens* may have been reduced (Pauly *et al*., 2002).

While the species appears to have resilient life history characteristics, the catch history suggests declining abundance. The high level of fishing in the mid-1950s in NSW may have resulted in a decrease in population abundance resulting in changes to life history characteristics such as smaller length at maturity, high growth rates and relatively short life-span (Cardoso & Haimovici, 2015) due to phenotype plasticity of the population (Brown-Peterson and Warren, 2001; Dieckmann and Heino, 2007; Cardoso and Haimovici, 2014).

The effects of overfishing on the sciaenid *Macrodon atricauda* has seen a decrease in maximum age and increased growth rates (exploited since the late-1950s) which is believed to be at the limit of reproductive stability increasing the species vulnerability to changes to recruitment. This may lead to a fishery collapse if fishing pressure increases or environmental changes occur (Longhurst, 2002 in Cardoso and Haimovici, 2015). There is a limit to resilience as there "are genetically determined boundaries to the plasticity of life history traits" (Dieckmann and Heino, 2007). If a similar pattern is occurring for *A. aequidens*, closer scrutiny of potential demographic changes through time will be required to avoid adverse effects of fishing on the population.

5.4 Further research

While intra-specific variations in reproductive traits such as size at maturity and duration and timing of the spawning season are common within the sciaenid family due to their cosmopolitan distribution (*A. japonicus*; Griffiths and Hecht, 1995b; Griffiths, 1997; Farmer *et al.*, 2005; Silberschneider and Gray, 2005, 2009; Ferguson and Ward, 2011), additional research comparing genetic stock structure between the Angolan, South Africa and Australian populations would provide insight to better understand the differences between the stocks and if speciation has occurred. The likelihood of the stock shared with QLD, could also be explored. Such vastly different life history characteristics and large geographical distances between the African and Australian populations suggest divergence between these populations and possible speciation.

Further analysis of commercial fisheries statistics such as CPUE data from the commercial handline fishery would provide an index of relative abundance to complement the development of a quantitative population assessment model. CPUE analysis would also be of use in determining the possible drivers of the substantial decline in fishing in areas south of Forster, that were once a major component of landings (see Chapter 2). It would be necessary to determine if the reason for this huge decline is either a shift in effort by commercial fishermen, evidence of localised depletions or a geographical shift caused by environmental factors or fishery-induced.

On a yearly scale (Figure 2.1.) it is clear there is a cyclical trend throughout the recorded commercial landings and analysing associations with state variables such as rainfall, catchment flow, Southern Oscillation Index, sunspot numbers and sea surface temperature using generalised linear models would provide greater insight to the variable recruitment patterns of *A. aequidens* in NSW. The likely impact of future climate scenarios on the productivity and resilience of the fishery could be explored.

The significantly different size distributions between the two regions requires further investigation to determine any depth related stratification of the commercial landings, or if there is an association with EAC on the growth and size structure of the two regions. Acoustic telemetry would determine connectivity of fish between the two study regions and in QLD and determine any evidence of site-fidelity which may have implications for management as the stock is currently managed state-wide.

5.5 Conclusion

This was the first study to determine the life history characteristics and describe the fisheries of *A. aequidens* in NSW. The species exhibits resilient life history strategies such as asynchronous oocyte development, year-round spawning and smaller length/age at maturity than many other sciaenids that are exploited. While the characteristics appear resilient the stock appears to be under heavy exploitation by fishing mortality as suggested by the shift in fishing regions, an age distribution based primarily on young fish and the long history of declining commercial landings. Fishing mortality is facilitated by the schooling nature and voracity of feeding of *A. aequidens* making it very susceptible to line fishing methods. Determination of the life history characteristics is paramount to the development of a stock assessment model which would enhance the management of *A. aequidens* in NSW.

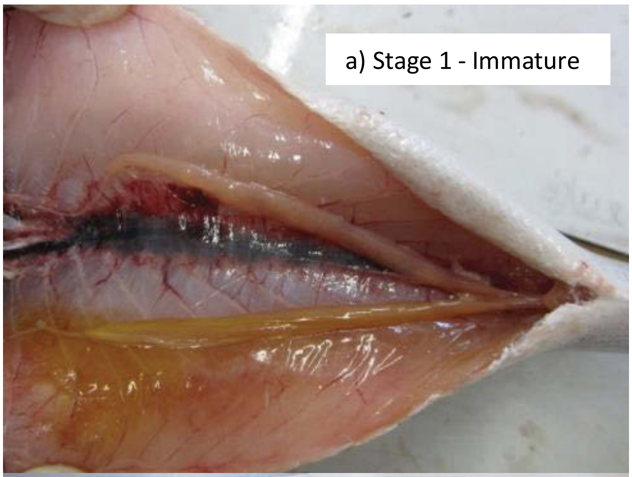
Appendix A

Comparison of life history characteristics for several sciaenid species. Note: L50 and A50 refer to length and age that 50% of the population reaches sexual maturity. **F:** females, **M:** males

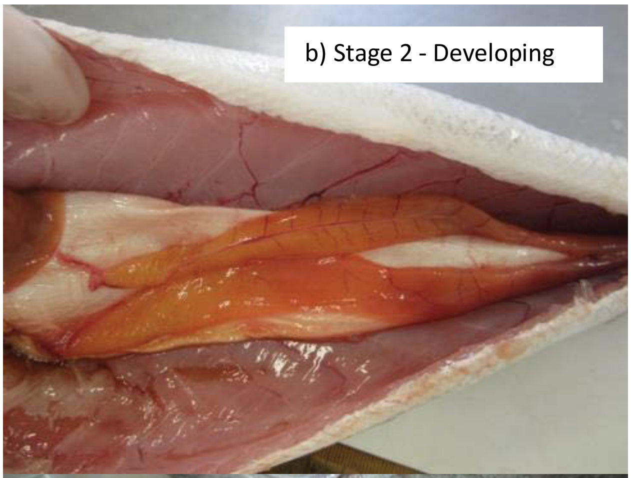
Common name	**Scientific name**	**Region**	**Max length, weight and age (recorded)**	**Spawning season**	**Length and age at maturity (L50, A50)**	**References**
Geelbek; Cape salmon	*Atractoscion aequidens*	southern Africa	130 cm TL, 25 kg, 9 yr	Peak in Spring to Summer	90 cm FL 5 yr	Griffiths and Hecht (1995a)
White sea bass	*Atractoscion nobilis*	West coast North America	160 cm TL, 40 kg, 25 yr	Peak in Spring to Summer	**F:** 70 cm TL **M:** 60 cm TL	Clark (1930), Thomas (1968), Donohoe (1997), Hervas *et al*. (2010)
Mulloway	*Argyrosomus japonicus*	NSW	132 cm TL, 42 kg. 24 yr	Summer to Autumn	**F:** 68 cm TL (+3 yr) **M:**51 cm TL male (+2 yr)	Silberschneider and Gray (2005) and 2009
Dusky cob	*Argyrosomus japonicus*	South Africa	181 cm TL, 75 kg, 42 yr	Winter to Spring	**F:** 107 cm TL (6 yr) **M:** 92 cm TL (5 yr)	Griffiths and Hecht (1995b), Griffiths (1997)
Mulloway	*Argyrosomus japonicus*	South Australia	41 years	Spring to Summer	**F:** 81 cm TL (6 yr) **M:** 81 cm TL (5 years)	Ferguson and Ward (2011)
Mulloway	*Argyrosomus japonicus*	Western Australia	144 cm TL, 31 yr (females) and 130 cm TL, 29 yr (males), 42,5 kg	Late spring – early summer	**F:** 93 cm TL (5-6 yr) **M:** 88 cm TL (5-6 yr)	Farmer *et al*. (2005)
Meagre	*Argyrosomus regius*	Gulf of Cadiz, Spain	200 cm, 42 years	Late winter – mid summer	**F:** 70-110 cm **M:** 61.6 cm	Gonzalez-Quiros (2011)
Southern kingfish	*Menticirrhus americanus*	Gulf of Mexico	35 cm TL, 4 years	6 months Spring to Summer	**F:** 17.1 cm (1+ years)	Clardy *et al* 2014
Spotted sea trout	*Cynoscion nebulosus*	Southern US	12 years 100 cm TL, 7.9 kg	Spring to summer (northern distribution) to a year (southern distribution)	**F:** 23-28 cm TL (0-1 yr), **M:** < 23-25 TL (0-1 yr)	Bortone (2003)
Striped weakfish	*Cynoscion guatucupa*	Atlantic coast South America	20-23 years	October to early April	32 cm	Fernandez-Iriarte *et al*. (2011)
Weakfish	*Cynsocion regalis*	Chesapeake Bay, Virginia	8.6 kg, 87.5 cm TL, 17 yr	May through August	1 yr old	Shepherd and Grimes 1984 in Lowerre-Barbieri *et al*. (1994)
Slender baardman	*Umbrina robinsoni*	South Africa	12kgs	November-March.Kosi bay had no clearly defined spawning period	**M:** 37 cm TL (3 yr) **F:** 39 cm TL (3.5 yr)	Hutchings and Griffiths, 2010

Appendix B

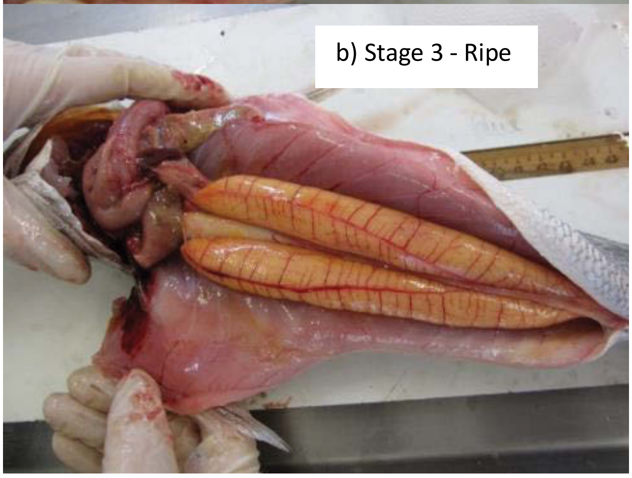
Female macroscopic criteria images for a) Stage 1 ‘immature’ b) stage 2 ‘developing/resting’, c) stage 3 ‘ripe’, d) stage 4 ‘running ripe’ and d) stage 5 ‘spent’



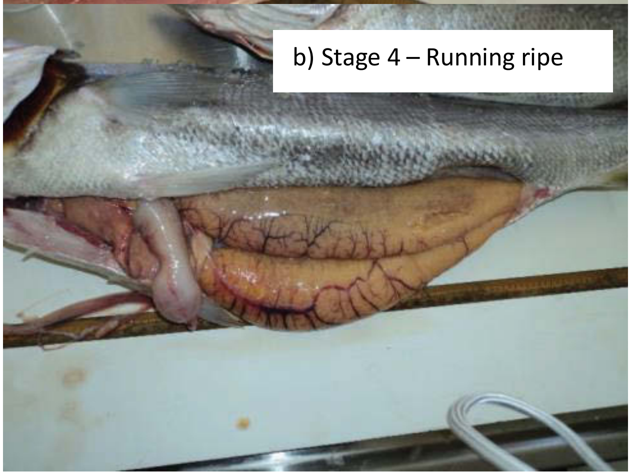
a) Stage 1 - Immature



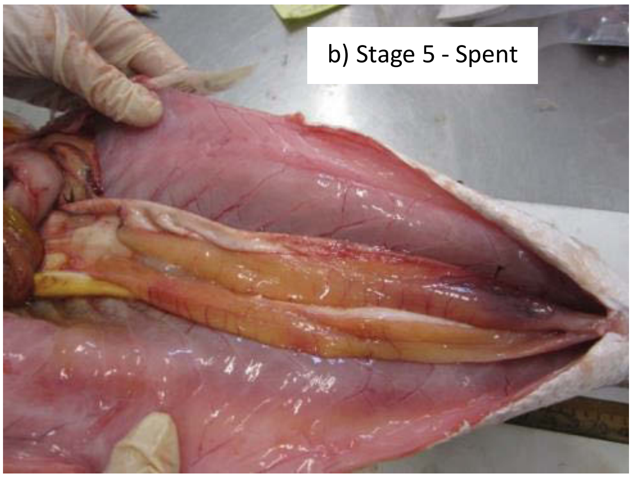
b) Stage 2 - Developing



b) Stage 3 - Ripe

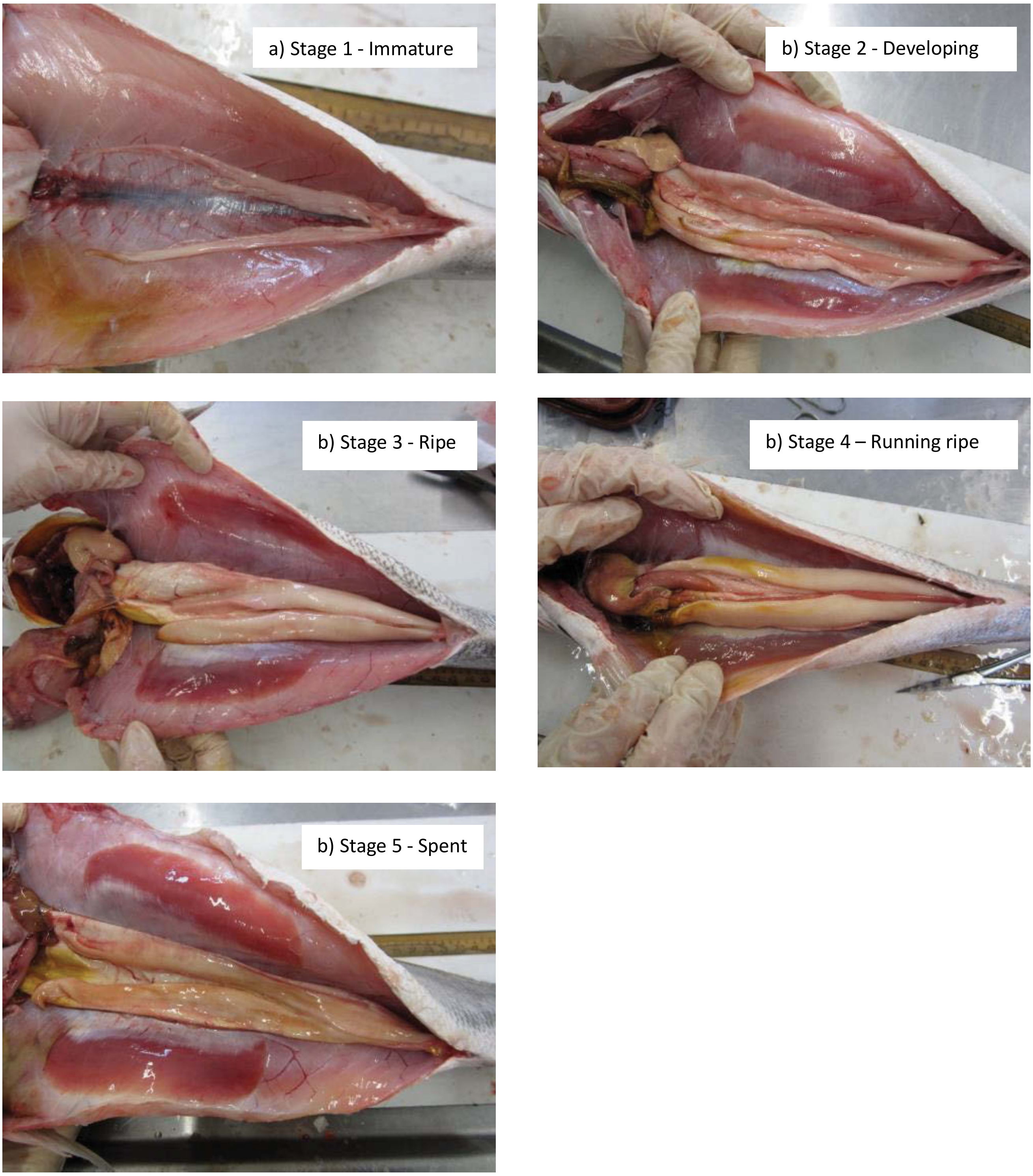


b) Stage 4 – Running ripe



b) Stage 5 - Spent

Male macroscopic criteria images for a) Stage 1 ‘immature’ b) stage 2 ‘developing/resting’, c) stage 3 ‘ripe’, d) stage 4 ‘running ripe’ and d) stage 5 ‘spent’



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